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ENDURANCE TESTING OF AN LM-726-4 ELASTOMERIC PITCH CHANGE BEARING

David L. Myers

Lord Kinematics

Prepared for:

Army Air Mobility Research and Development Laboratory

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David L. Myers
Lord Kinematics
A Division of Lord Corporation
Erie, Pa. 16512

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Approved for public release;
distribution unlimited.

Prepared for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
Fort Eustis, Va. 23604

EUSTIS DIRECTORATE POSITION STATEMENT

The conclusions contained herein are concurred in by this Directorate; however, it should be noted that the life demonstrated in these tests is a value indicative of the bench test life. Another elastomeric bearing configuration presently undergoing flight tests has already exceeded its bench test life by a factor of 4 and has yet to indicate the initiation of failure.

The technical monitor for this contract was Mr. John W. Sobczak, Military Operations Technology Division.

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Presented in this report are the results of a 2000-hour endurance test on the LM-726-4 elastomeric pitch change bearing designed for the all-elastomeric rotor in the AH-1G helicopter. The LM-726-4 is an improved version of a previously tested pitch change bearing incorporating several design modifications with the goal of improving fatigue life. Testing was conducted to form a basis for determining the airworthiness of the bearing in terms of expected reliability and inspection and replacement criteria.

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Endurance testing was conducted on six LM-726-4 bearings in a test machine specifically designed to impose the load and motions expected in normal service. The load and motion spectrum utilized was determined by an AH-1G flight test program conducted on a conventional rotor and on a prototype all-elastomeric rotor. All testing was performed at room temperature. Periodic inspections of the bearings' performance characteristics were conducted at 200-hour intervals to monitor their condition.

The endurance test procedure is briefly discussed, and the results of the periodic testing are prese l in detail. Three of the six samples were tested to ailure, and the modes of failure are discussed. Recommendations are made for the inspection and replacement of elastomeric bearings based on the tests conducted. The testing has demonstrated the validity of the design modifications with the projected Weibull B-10 life of the bearing in excess of 1800 hours. The results indicate that the LM-726-4 is suitable for field service evaluation.

PREFACE

This report presents the results of tests performed by Lord Kinematics under Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory (USAAMRDL) Contract DAAJ02-72-C-0091 (DA Project 1F163204DB38).

The work was conducted under the technical cognizance of Mr. John Sobczak of the Eustis Directorate, USAAMRDL. Principal Lord personnel involved in the program were Messrs. J. Gorndt, J. Grantham, D. Myers, and J. Potter. In addition, technical assistance was received from Messrs. W. Cresap, C. Fagan, W. Neathery, and R. Pascher of Bell Helicopter Company.

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INTRODUCTION

Elastomeric bearings are being utilized to an increasing extent in helicopter rotor applications to replace conventional rolling element bearings. The use of elastomeric bearings offers significant advantages to the helicopter operator. Complex bearing lubrication systems can be eliminated, resulting in a reduction of maintainence requirements. Laboratory and flight evaluations of elastomeric bearings have demonstrated service lives which exceed those experienced with conventional bearings. Their greater reliability will reduce both scheduled and unscheduled maintainence of helicopter rotor systems. Design studies of new rotor systems have shown that proper utilization of the elastomeric bearing concept can provide a significant reduction in rotor components, profile and weight.

Elastomeric bearings utilize a "high capacity" concept which allows accommodation of oscillatory motions through elastomer shear while carrying relatively high steady and oscillatory loads in the elastomer compression direction. Since elastomers are incompressible, compression deflections, and therefore compression strain, can occur only if the free surface of the elastomer is allowed to bulge. Proper selection of an elastomer layer's thickness to provide the desired ratio of load area to bulge area allows the designer to control compression load-carrying capacity. By alternating the elastomer layers with metal shims to obtain a laminated element, the designer can obtain the desired shear capabilities in the elastomeric bearing design.

The LM-726-4 elastomeric bearing is a conical configuration designed to accommodate the loads, motion and life requirements of the Bell Helicopter Model 540 Rotor System. Two LM-726-4 bearings are utilized to equally share the blade centrifugal force along the bearings' conical axis. Steady and oscillatory radial loads resulting from blade moments are reacted by each bearing perpendicular to the cone axis. Blade pitch change motion, steady and oscillatory, is accommodated through torsional shear of the elastomer about the cone axis.

A limited laboratory and flight test evaluation jointly conducted in late 1970 and early 1971 by Bell Helicopter Company and Lord Kinematics, under Eustis Directorate, USAAMRDL sponsorship, demonstrated the feasibility of the conical bearing concept as applied to the above-mentioned

rotor system. This testing was conducted on the LM-726-1 bearing, and the results are contained in USAAVLABS Technical Report 71-16.[1]

Additional laboratory testing of the LM-726-1 bearing was conducted to determine its expected service life. Loads and motions based on actual in-flight measurements of the standard and on the prototype Model 540 All-Elastomeric Rotor System were imposed on six LM-726-1 test specimens. Environmental conditions typical of those expected in service were selected and imposed on the bearings simultaneously with the fatigue conditions. Failures occurred in the range of 800 to 1400 hours, resulting in a Weibull B-10 life of 812 hours. This testing indicated a need for an improved fatigue life bearing which was designed to provide a 50% improvement in fatigue life. The results of laboratory fatigue testing conducted on the LM-726-1 bearing are contained in USAAMRDL Technical Report 72-73.[2]

Several design modifications were incorporated into the LM-726-4 elastomeric bearing to provide an improved fatigue life. A slight increase in the available space envelope permitted an increase in the amount of flexing elastomer, resulting in an overall reduction in operating shear strains. The contour of the flexing element was modified to provide a more direct radial load-carrying capability. The major metal parts utilized for attachment purposes were modified as required to be compatible with the requirements of the redesigned Model 540 Rotor components.

A 2000-hour endurance test was conducted on six LM-726-4 test samples. The loads and motions utilized were identical to those imposed on the LM-726-1 bearing during previous testing. All testing was performed at room temperature in order to directly evaluate the effects of the design modifications.

TEST SAMPLES

The LM-726-4 bearing design included several product improvement features which resulted from testing of the LM-726-1 bearing. The goal of the product improvement modifications was to provide a 50-percent or greater improvement in laboratory fatigue life without significantly altering the bearing's spring rate characteristics. This goal was achieved in that the fatigue life of the LM-726-4 exceeded the goal and its performance characteristics were approximately identical to the LM-726-1.

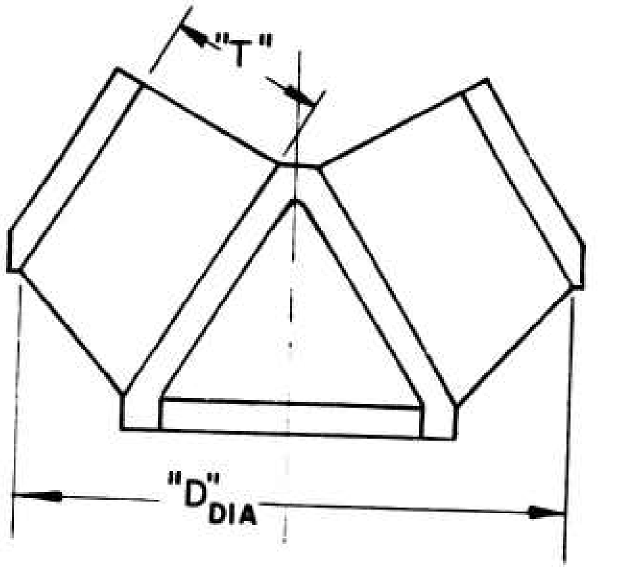
Figure 1 is a comparison of the cross sections of the LM-726-1 and LM-726-4 bearings. Both the inner and outer major metal attachment members are more detailed than shown in these outlines; however, the interfaces with the elastomer and metal shim flexing element are of primary interest in this discussion.

Both the LM-726-1 and LM-726-4 have inner members identical in size at the interface with the flexing element. Ideally, the inner member of the LM-726-4 would have been larger in order to reduce the elastomer compression stress as a means of improving fatigue life. However, analytical design studies indicated that any increase in inner member size would greatly increase the torsional spring rate which was undesirable.

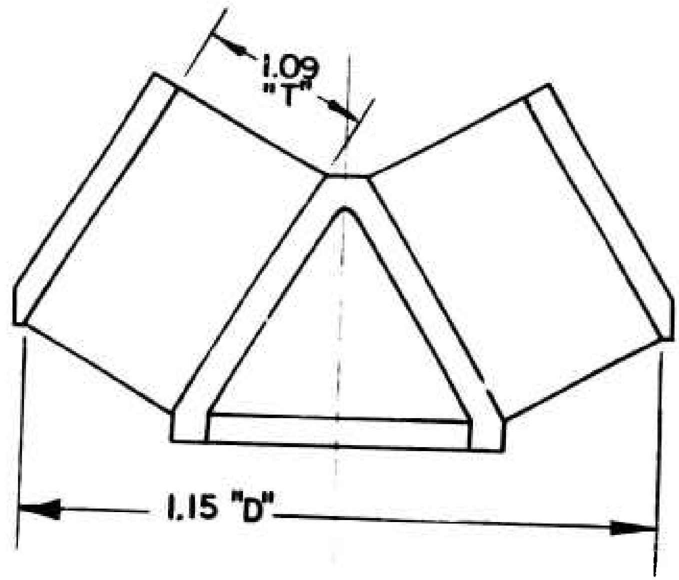
The allowable space envelope for the LM-726-4 was greater than that of the LM-726-1. This allowed a larger outer diameter for the flexing element as can be seen by examination of Figure 1. Two modifications contributed to the increase in outer diameter: the overall increase in the thickness of the laminate and the change in its profile. These two modifications combined to result in a 15-percent larger outer diameter with the LM-726-4 bearing.

The thickness of the laminate, dimension "T" of Figure 1, is 9 percent greater on the LM-726-4 as compared to the LM-726-1. This increase in overall thickness when coupled with a reduction in the individual shim thickness allowed a 22-percent increase in total elastomer thickness. The increase in the thickness of elastomer resulted in a overall reduction in operating shear strains which contributed to the increase in fatigue life.

The cross-sectional profile of the LM-726-1 was trapezoidal in shape as can be seen from Figure 1. This was done in order to minimize the outermost diameter of the flexing



LM-726-1 Cross-Section View
- Tapered Section Length
- Trapezoidal Profile
- Thickness of Elastomer = T_R



LM-726-4 Cross-Section View
- Constant Section Length
- Rectangular Profile
- Thickness of Elastomer = 1.22 T_R

Figure 1. Cross-Sectional Comparison of LM-726-1 and LM-726-4.

element. Fatigue testing of the LM-726-1 bearing indicated that the radial loading was a primary cause of premature failure since initial failure indications were located directly in line with the radial load. The tapered length of the flexing element resulting from its trapezoidal shape was considered to provide inadequate support for radial loads. As a result, the LM-726-4 utilizes a constant length elastomer section which results in its rectangular profile. Although this modification resulted in a larger outer diameter, it was incorporated to provide a direct radial load path from the inner to outer attachment metal part. This resulted in an improved capability for supporting radial loads which directly contributed to the increase in fatigue life.

Thirty-four LM-726-4 elastomeric bearings were manufactured and allocated as shown in Table I. Two special versions of the LM-726-4 were manufactured and designated LM-726-4-1 and LM-726-4-2. The LM-726-4-1 bearing was utilized for endurance testing. The elastomeric flexing element of this version is identical to the LM-726-4; however, the inner attachment member configuration from the LM-726-1 was retained in order to minimize test fixture modifications. This modification did not affect the results of endurance testing. The LM-726-4-2 bearing utilized BTR VIII elastomer in place of natural rubber used in the standard LM-726-4 bearing. This modification was made to provide improved low-temperature performance characteristics for cold-weather tests to be performed.

After serialization, static torsional and axial load versus deflection tests were performed on each sample individually. The results are summarized in Table II. The torsional testing of the eight endurance test samples and serial numbers 065 and 082 was performed in a manner slightly different from the remaining bearings. These bearings were loaded through $\pm 20°$ of motion, and the torque at +15° was used to obtain the spring rate value. The remaining bearings were loaded from 0° to +20° and back to 0°. The spring rate was again obtained at 15°. The different loading method accounts for the lower spring rates measured on the endurance samples, rather than an actual difference in performance characteristics. The six BTR VIII samples were purposely designed to have a lower static torsional spring rate when compared to the standard natural rubber LM-726-4. The nominal torsional spring rate of the eight endurance test samples and serial numbers 065 and 082 was 158.25 in.-lb/deg, with a variation of ± 4.25 in.-lb/deg or $\pm 2.7\%$. The remaining samples,

tested by a different method, were 174.15 in.-lb/deg with a variation of ±10.85 in.-lb/deg, a variation of 6.2%. The six BTR VIII parts were nominally 135.75 in.-lb/deg with a variation of ±5.75 in.-lb/deg, or 4.2%.

The axial spring rate measurements were performed in a consistent manner on all test bearings. The nominal axial deflection at the normal centrifugal force of 56,000 lb was .103 in. with variation of ±.004 in., or 3.9%. The six BTR VIII parts deflected .105 in. with a variation of ±.002 in., or 1.9%. Table II contains the axial spring rate values which result from these deflections.

Figure 2 is a typical torsional load versus deflection curve for an LM-726-4 bearing. Typical load versus deflection curves in the axial direction for this same bearing are shown in Figure 3. Upon completion of load versus deflection testing, all samples were inspected for compliance with the drawing shown in Figure 4 prior to further testing.

TABLE I. ALLOCATION OF TEST SAMPLES		
Bearing Serial Number	Part Number	Allocation
004	LM726-4-1	Endurance Test Bearing-Test Sample 1
005	LM726-4-1	Endurance Test Bearing-Test Sample 2
006	LM726-4-1	Endurance Test Bearing-Test Sample 3
009	LM726-4-1	Endurance Test Bearing-Test Sample 4
014	LM726-4-1	Endurance Test Bearing-Test Sample 5
016	LM726-4-1	Endurance Test Bearing-Test Sample 6
018	LM726-4-1	Endurance Test Bearing-Spare
019	LM726-4-1	Endurance Test Bearing-Spare
024	LM726-4	Delivered to Bell Helicopter Company
026	LM726-4	Delivered to Bell Helicopter Company
027	LM726-4	Delivered to Bell Helicopter Company
041	LM726-4	Delivered to Bell Helicopter Company
042	LM726-4	Delivered to Bell Helicopter Company
043	LM726-4	Delivered to Bell Helicopter Company
047	LM726-4	Delivered to Bell Helicopter Company
057	LM726-4	Delivered to Bell Helicopter Company
058	LM726-4	Delivered to Bell Helicopter Company
059	LM726-4	Delivered to Bell Helicopter Company
061	LM726-4	Delivered to Bell Helicopter Company
064	LM726-4	Delivered to Bell Helicopter Company
071	LM726-4	Delivered to Bell Helicopter Company

TABLE I - CONTINUED

Bearing Serial Number	Part Number	Allocation
072	LM726-4	Delivered to Bell Helicopter Company
075	LM726-4	Delivered to Bell Helicopter Company
076	LM726-4	Delivered to Bell Helicopter Company
081	LM726-4	Delivered to Bell Helicopter Company
084	LM726-4	Delivered to Bell Helicopter Company
029	LM726-4-2	BTR VIII Bearing-Delivered to Bell
031	LM726-4-2	BTR VIII Bearing-Delivered to Bell
050	LM726-4-2	BTR VIII Bearing-Delivered to Bell
080	LM726-4-2	BTR VIII Bearing-Delivered to Bell
055	LM726-4-2	BTR VIII Bearing-Delivered to Government
056	LM726-4-2	BTR VIII Bearing-Delivered to Government
082	LM726-4	Delivered to Government
065	LM726-4	Delivered to Government

TABLE II. SPRING RATES OF TEST SAMPLES					
Bearing Serial Number	Material	Torque at 15°	Torsional Spring Rate	Axial Defl'n @ 56K Lb	Axial Spring Rate
029	BTR VIII	1950	130.0	.107	523,000
031	BTR VIII	1975	131.7	.103	543,000
050	BTR VIII	2025	135.0	.106	528,000
055	BTR VIII	2125	141.7	.103	543,000
056	BTR VIII	2050	136.7	.104	538,000
080	BTR VIII	2000	133.3	.104	538,000
024	Natural Rubber	2650	176.7	.099	565,000
026	Natural Rubber	2750	183.3	.103	543,000
027	Natural Rubber	2775	185.0	.102	549,000
041	Natural Rubber	2650	176.7	.102	549,000
042	Natural Rubber	2700	180.0	.100	560,000
043	Natural Rubber	2650	176.7	.101	554,000
047	Natural Rubber	2450	163.3	.102	549,000
048	Natural Rubber	2725	181.7	.103	543,000
057	Natural Rubber	2675	178.3	.102	549,000
058	Natural Rubber	2725	181.7	.099	565,000
059	Natural Rubber	2725	181.7	.099	565,000
061	Natural Rubber	2725	181.7	.103	543,000
064	Natural Rubber	2650	176.7	.105	533,000
065	Natural Rubber	2350	156.6	.100	560,000
071	Natural Rubber	2650	176.7	.102	549,000

TABLE II - CONTINUED					
Bearing Serial Number	Material	Torque at 15°	Torsional Spring Rate	Axial Defl'n @ 56K Lb	Axial Spring Rate
072	Natural Rubber	2675	178.3	.103	543,000
075	Natural Rubber	2625	175.0	.102	549,000
076	Natural Rubber	2625	175.0	.102	549,000
081	Natural Rubber	2700	180.0	.103	543,000
082	Natural Rubber	2350	156.6	.102	549,000
084	Natural Rubber	2625	175.0	.101	554,000
004	Natural Rubber	2312	154.0	.105	533,000
005	Natural Rubber	2412	160.8	.105	533,000
006	Natural Rubber	2437	162.5	.103	543,000
009	Natural Rubber	2437	162.5	.100	560,000
014	Natural Rubber	2425	161.7	.102	549,000
016	Natural Rubber	2437	162.5	.103	543,000
018	Natural Rubber	2375	158.3	.103	543,000
019	Natural Rubber	2412	160.8	.107	523,000

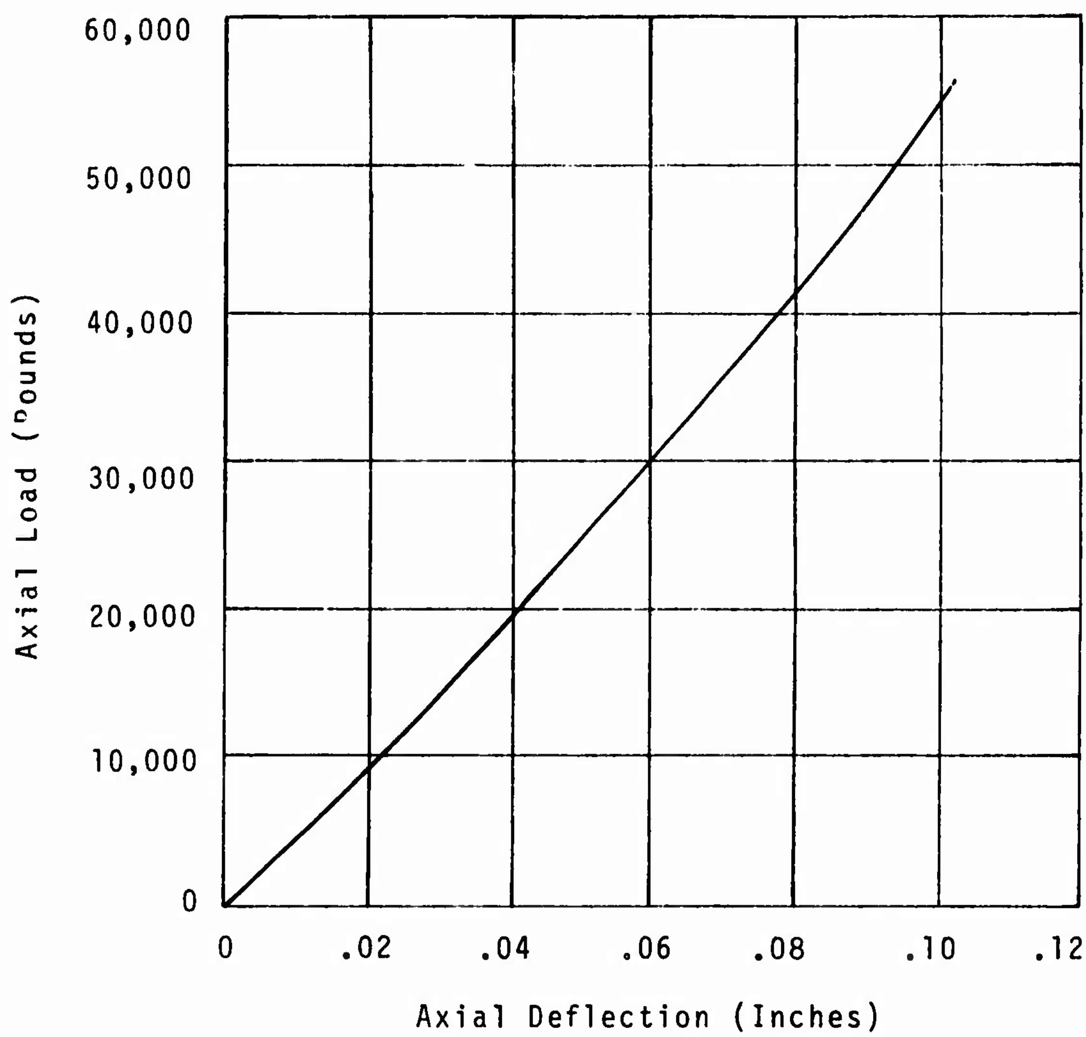


Figure 2. Axial Spring Rate of LM726-4, S/N 071.

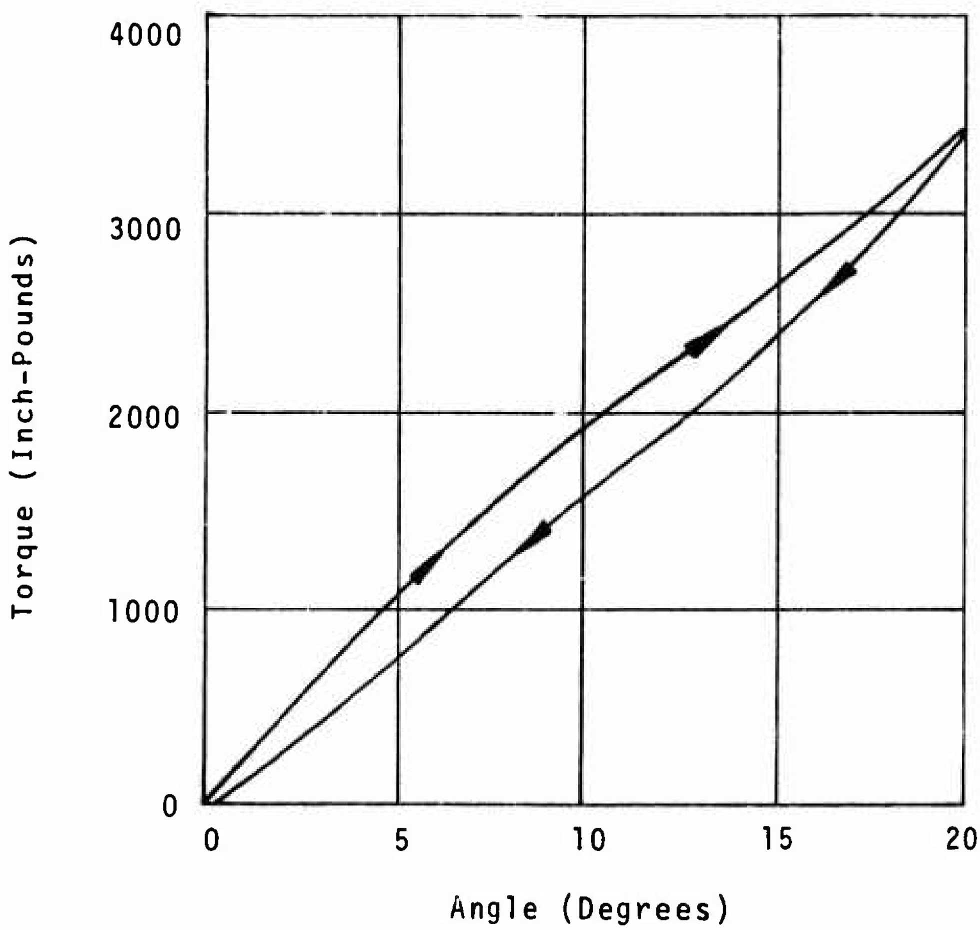


Figure 3. Torsional Spring Rate of LM726-4, S/N 071.

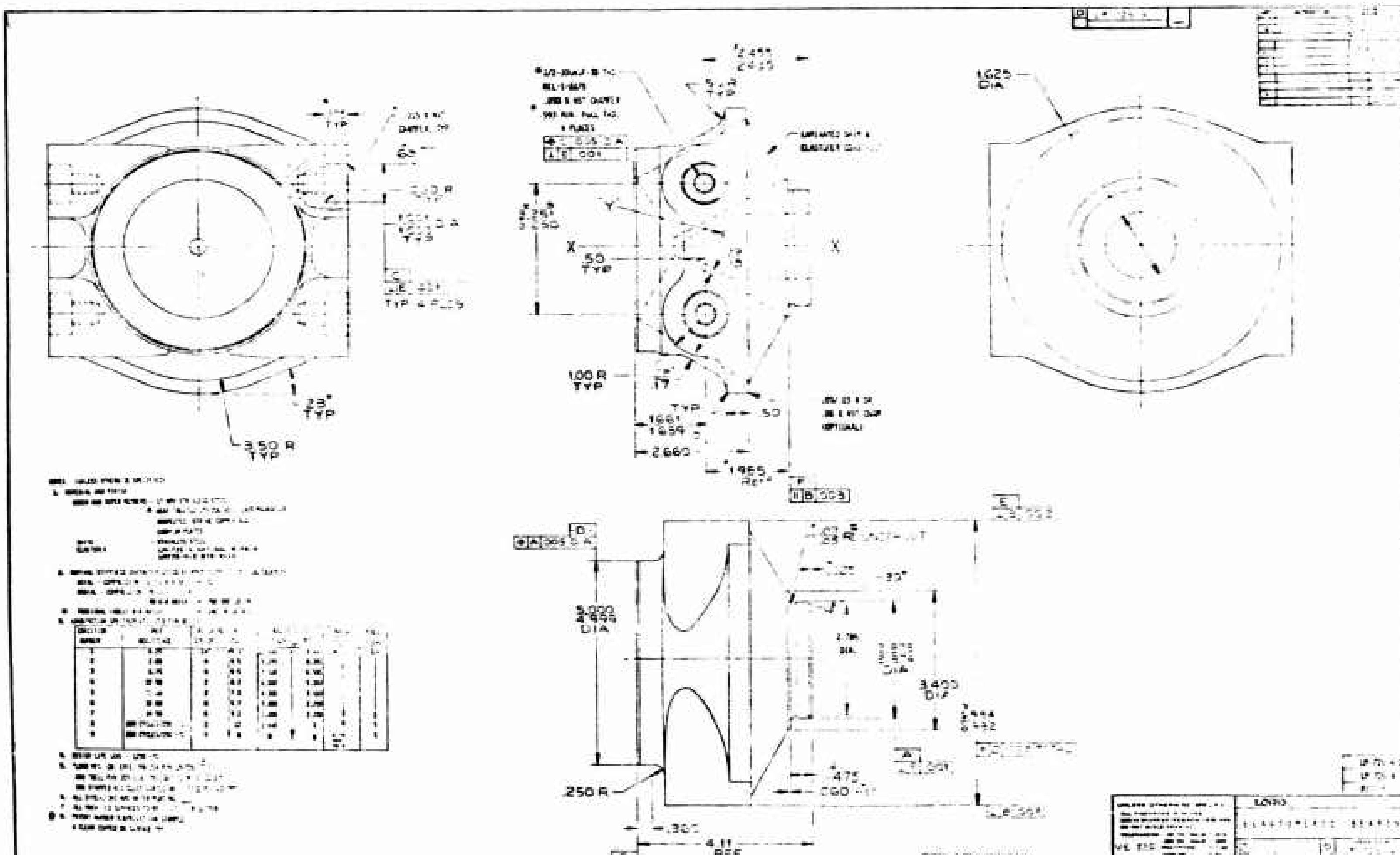


Figure 4. Elastomeric Pitch Change Bearing LM-726-4.

ENDURANCE TESTING

ENDURANCE TEST PROCEDURE

Eight LM-726-4-1 test samples were delivered to the test laboratory for use as endurance test samples. Six of these bearings were selected and subjected to the zero-hour periodic inspection. The remaining two samples were retained for use as spares to replace failed samples and to allow testing to continue.

Upon completion of the initial periodic inspection, the six endurance test samples were installed in the endurance test machine as shown in Figure 5. The samples were installed in pairs at each of three test stations. The samples remained in these positions throughout the endurance test except when removed for periodic inspections.

A test spectrum recycling block of 40 hours was selected in order to maintain a direct comparison to previous LM-726-1 data. The sequence of application of the endurance test conditions was as shown in Table III. This sequence was selected during the LM-726-1 endurance test to minimize internal heating of the test samples.

In the actual application of the LM-726-4 bearings, input conditions of relatively large magnitude which result in internal heating of the bearings are of short duration. In addition, rotor airflow characteristics result in a large amount of cooling air circulating around the bearings. By sequencing the test conditions to alternate severe conditions with those less severe and by the use of small fans at each station, an attempt was made to duplicate service conditions.

Endurance testing was completed in 200-hour blocks. After completion of the initial 200 hours of cycling, consisting of five 40-hour test blocks, the manual conditions listed in Table III were applied. These conditions are applied manually at low frequency.

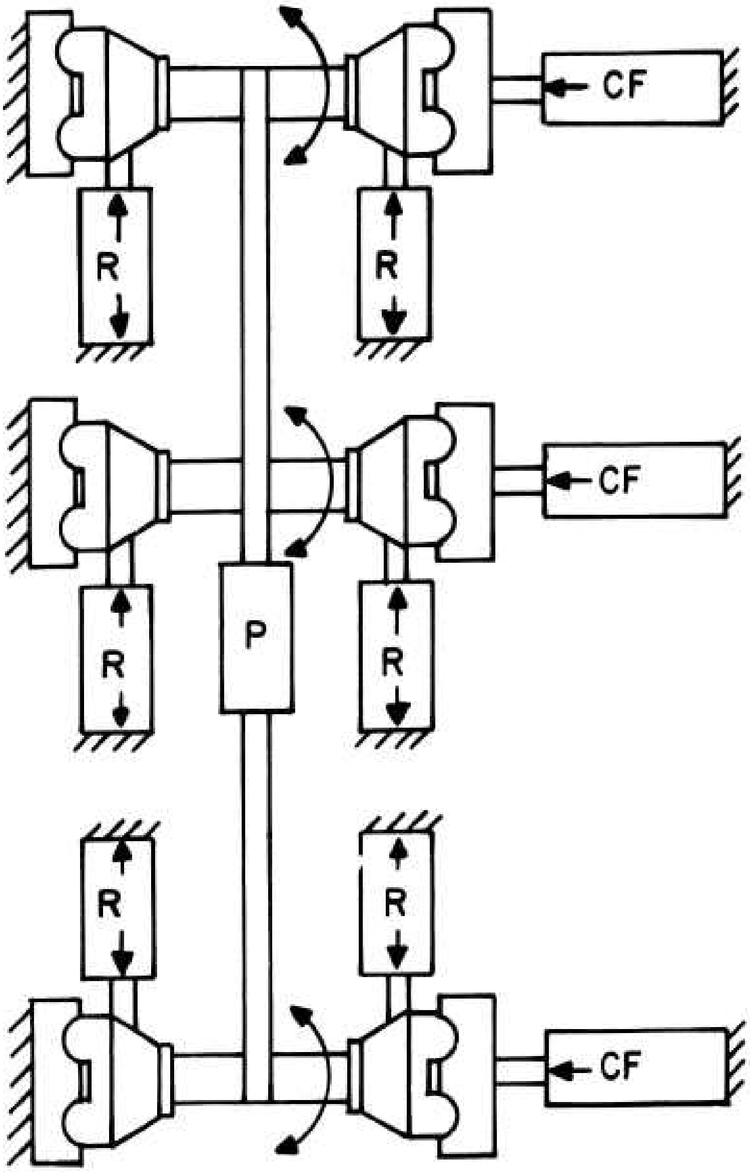
The first manual condition listed represents extreme pitch change motion applied without centrifugal force to simulate an on-ground check of control motion. The second condition simulates rotor start-up to full rotor speed and subsequent shutdown.

Upon completion of the manual conditions, the 200-hour periodic inspection was performed. The test samples were

removed from the endurance test machine and subjected to static spring rate testing in the torsional and axial directions. The static torsional test consisted of an input from 0° to -20° back through 0° to +20° and returning to the original position. This test was performed without axial load on the bearing at a loading speed of 20 degrees per minute. The axial test consisted of a 0 to 56,000-lb loading in the centrifugal force direction at .125-in. per minute. Each test sample was then photographed and dimensionally inspected in accordance with the test plan. The dimensions inspected were selected to determine changes in the flexing element by measuring the relationship between major metal components.

The test samples were reinstalled in the test machine at the same location and in the identical orientation for continuation of the test. Periodic inspections were performed at 200-hour intervals until the 2000-hour level, at which time the final periodic was performed and testing was terminated.

The failure criterion for the test samples was arbitrarily established as a 40% decrease in static torsional spring rate from the zero-hour value. Among the other potential failure criteria were broken shims, inability to support radial or axial loads, excessive loss of elastomer creating metal-to-metal contact, and failure of a major metal component.



CF - Centrifugal Force
R - Radial Load
P - Pitch Motion

Figure 5. Location of Test Samples in Endurance Test Machine.

TABLE III. LOADS AND MOTIONS FOR ENDURANCE TEST

Condition Number	Test Sequence	Percent Occurrence	Axial Load (lb)	Radial Load (lb) Steady	Radial Load (lb) Osc.	Pitch Motion (deg) Steady	Pitch Motion (deg) Osc.	Dynamic Frequency (cpm)
1	5	0.25	56,000	10000	±9400	14	±9.5	324
2	7	6.75	56,000	9000	±8000	4	±9.5	324
3	2	2.00	56,000	7000	±6500	4	±9.5	324
4	6	22.50	56,000	6000	±5000	2	±8.2	324
5	3	22.00	56,000	4000	±3600	2	±7.0	324
6	1	32.00	56,000	3000	±2200	0	±5.7	324
7	4	14.50	56,000	2000	±2200	6	±3.2	324
1M	-	800 cycles/200 hours	0	2640	-	0	±12	5
2M	-	800 cycles/200 hours	0 to 56000	0	0	0	0	5

Note: Conditions 1M and 2M are referred to as "manual" conditions since they are not under automatic control and are applied by hand at low frequency after each 200-hour block.

ENDURANCE TEST MACHINES

The test machine used for the endurance test of the LM-726-4 is shown in Figure 6. All three test stations can be seen in this photograph. The test samples are for the most part hidden from view. Figure 6 is a closeup of one of the three test stations. The test machine is designed to hold the sample outer member fixed with respect to torsional motion while rotating the sample inner member through the required pitch motion.

The periodic static torsional and axial spring rate tests were performed in separate test machines. Each sample together with a portion of the endurance test machine structure was installed in the torsional test stand shown in Figure 8. A hydraulic cylinder applied the required torque to achieve the desired $\pm 20°$ of pitch motion. The test sample and structure were then placed in a universal test machine as shown in Figure 9 for performance of the axial load versus deflection test. The axial load was applied through the inner member, and the deflection was measured with an LVDT, visible in the center of the photograph below the test sample.

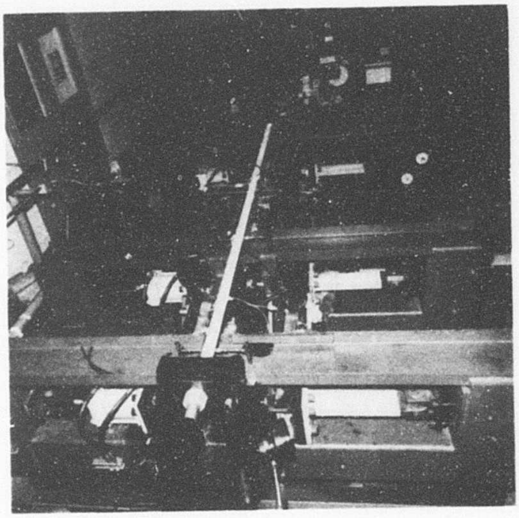


Figure 6. Overall View of Endurance Test Machine, Showing Three Test Stations. (Centrifugal force cylinders are visible on left, and test sample 2 is visible in center foreground.)

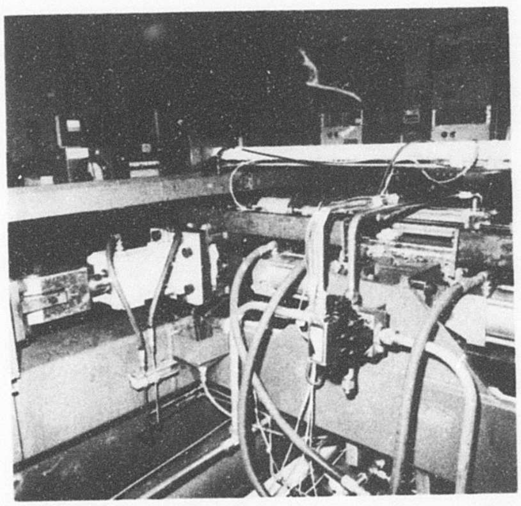


Figure 7. Closeup View of Endurance Test Station, With Outer Member of Test Sample 5 Partially Visible in Center of Photograph. (Light-colored cylinder applies centrifugal force. Radial load cylinder is located in center of picture. Pitch cylinder is on top of machine in right center of photograph.)

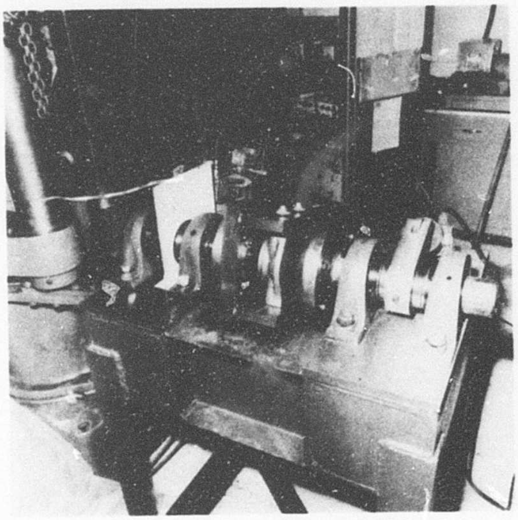


Figure 8. Test Stand for Periodic Testing of Sample Torsional Spring Rate.

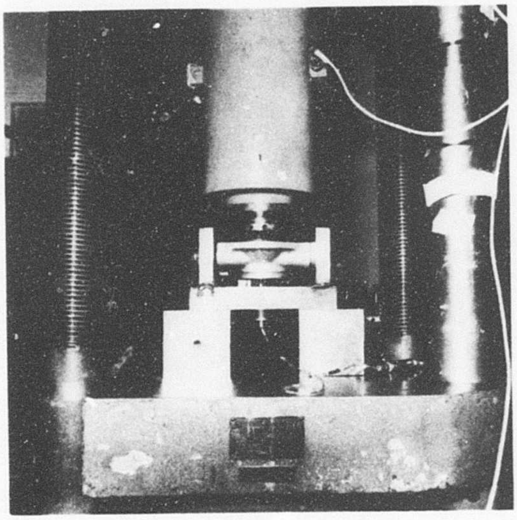


Figure 9. Periodic Axial Spring Rate Test in Universal Testing Machine.

ENDURANCE TEST RESULTS

PERIODIC STATIC SPRING RATES OF INDIVIDUAL SAMPLES

The results of the periodic axial and torsional load versus deflection tests of the six endurance test samples are contained in Figures 10 through 23. The axial spring rate value was obtained by dividing the normal centrifugal force load of 56,000 lb by the axial deflection obtained at that load. The value shown as the torsional spring rate is the peak-to-peak torque divided by the peak-to-peak deflection of 40°.

Figures 22 and 23 are the axial and torsional spring rate envelopes into which all six samples fall. These envelopes are relatively narrow, indicating that all six samples performed consistently. The rate of degradation was uniform for all six endurance test samples. Figure 22 illustrates the gradual decrease in axial spring rate of the test samples which occurred over the 2000 hours of testing. The spring rates at 2000 hours were approximately 20% below the initial values. The torsional spring rates did not show the same downward trend, although test sample 3 did decrease rapidly between the 1800-hour and 2000-hour periodic inspection. The loss of elastomer in the innermost section of the bearing was the primary factor affecting spring rates. Table IV contains the static torsional spring rates of the individual samples.

PERIODIC STATIC TORSIONAL SPRING RATES OF SAMPLE PAIRS

The torsional spring rate of each test sample pair was measured while the samples were installed in the test machine. The normal centrifugal force of 56,000 lb was applied to the bearings during measurement.

The resulting spring rate values are contained in Table V. This data is of limited value since the torsional spring rates of individual samples without centrifugal force are believed to be more accurate and a better indicator of sample condition. With the exception of erratic data at 800 and 1000 hours, there is little change in the sample spring rates.

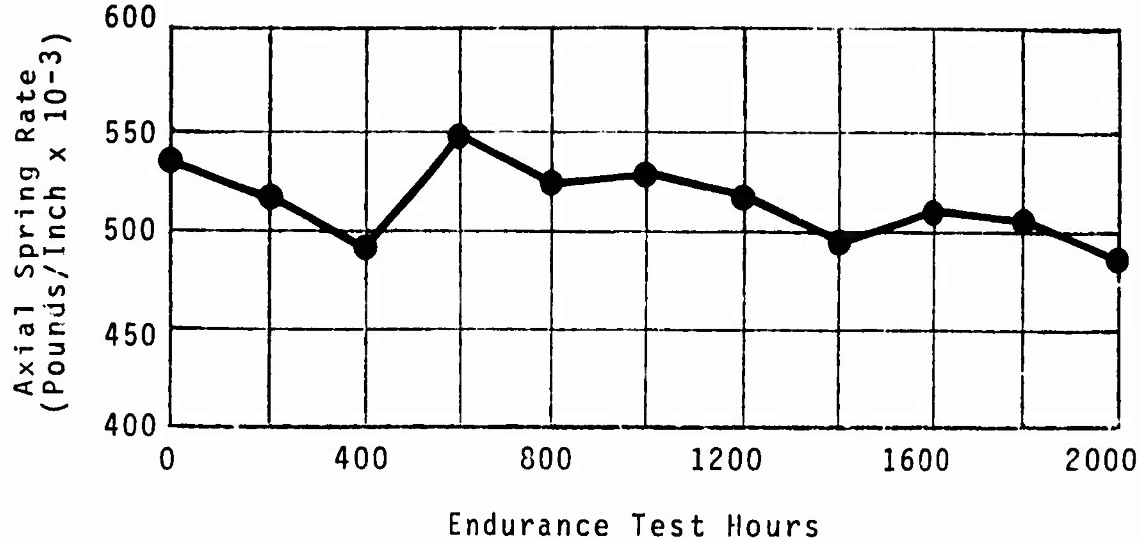


Figure 10. Static Axial Spring Rate of Test Sample 1 (S/N 004).

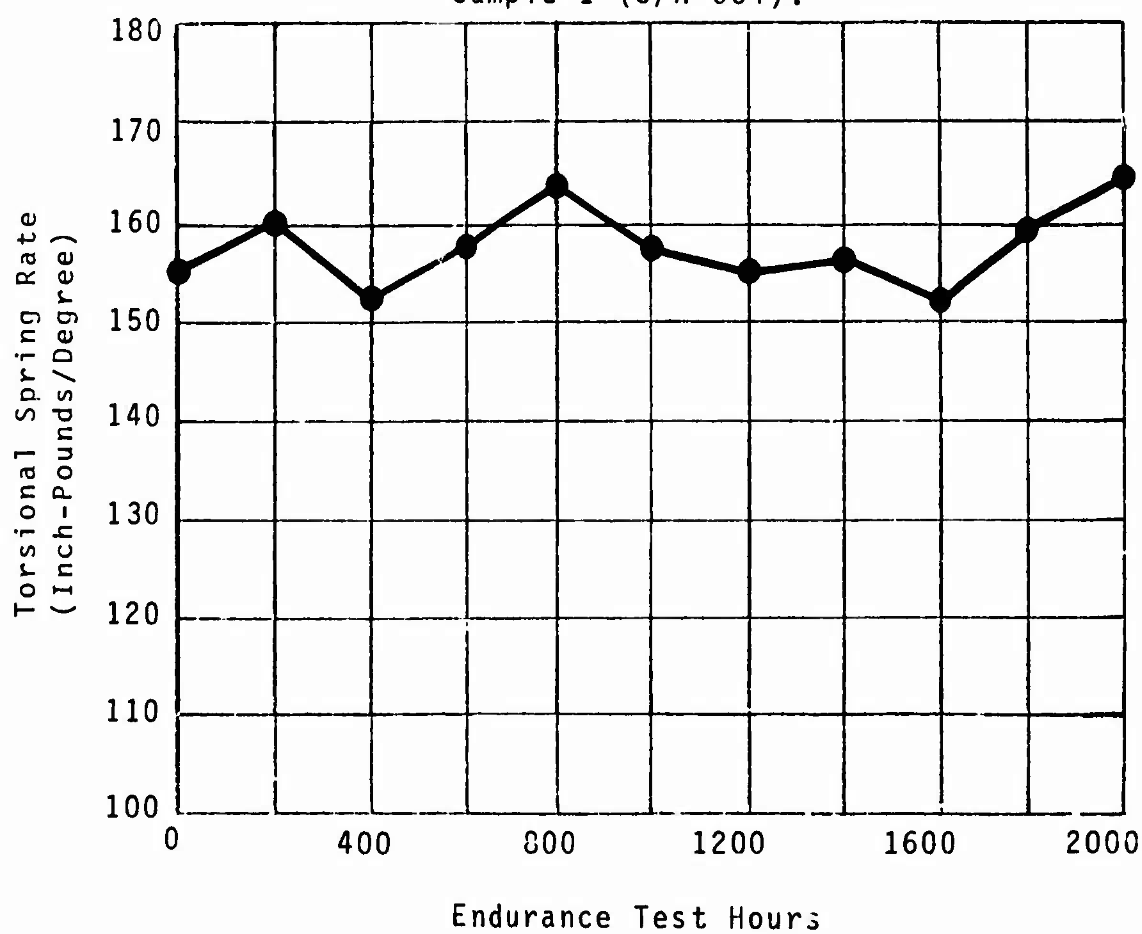


Figure 11. Static Torsional Spring Rate of Test Sample 1 (S/N 004) Without CF Applied.

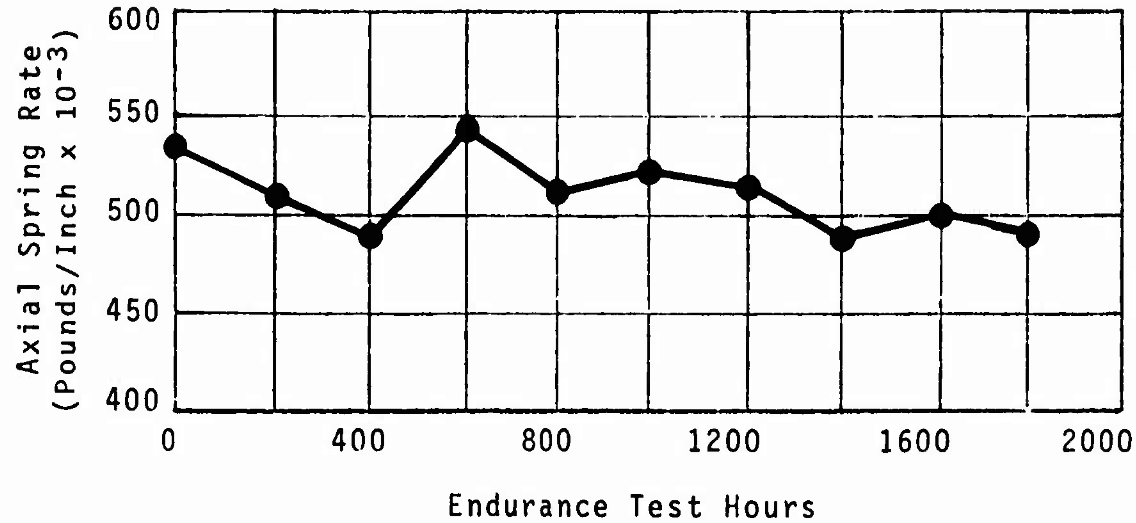


Figure 12. Static Axial Spring Rate of Test Sample 2 (S/N 005).

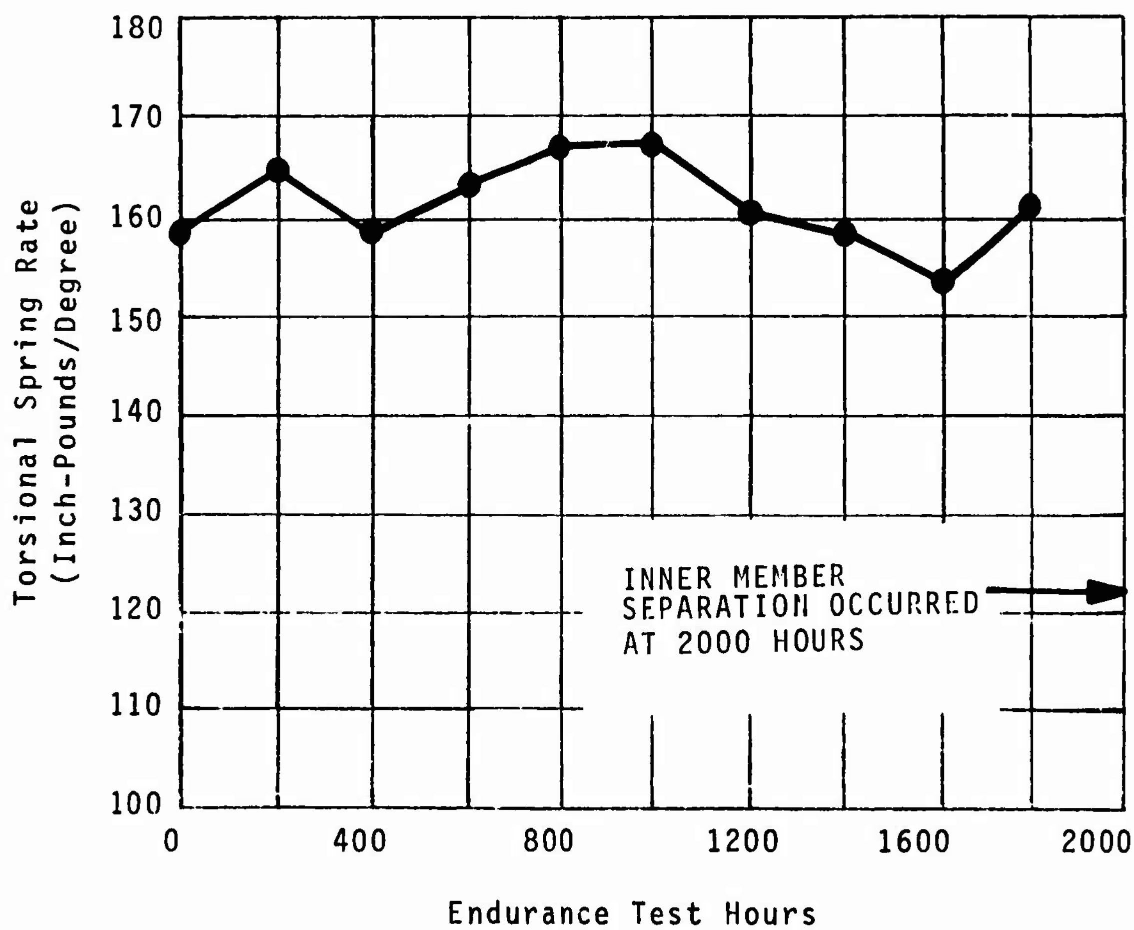


Figure 13. Static Torsional Spring Rate of Test Sample 2 (S/N 005) Without CF Applied.

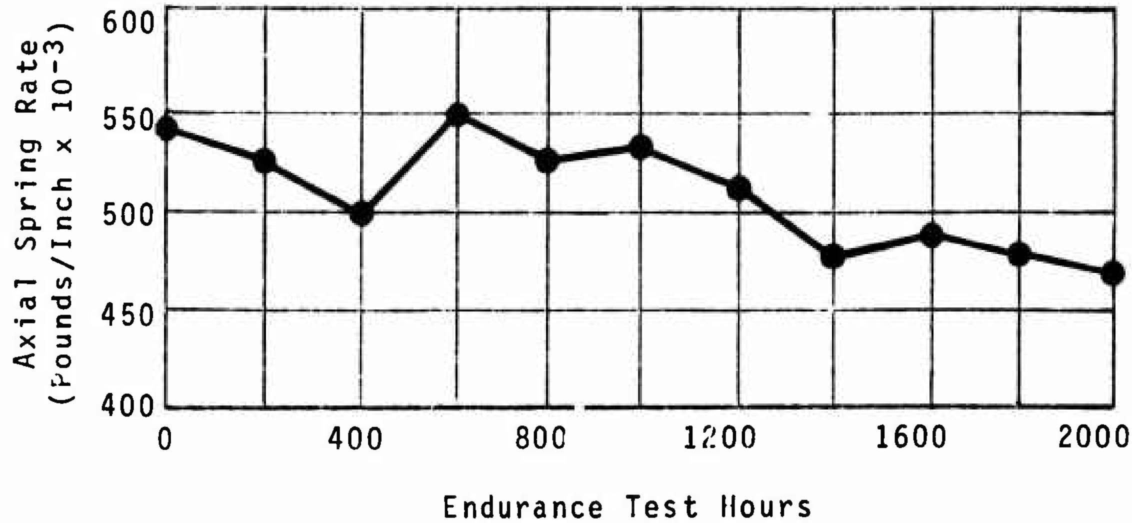


Figure 14. Static Axial Spring Rate of Test Sample 3 (S/N 006).

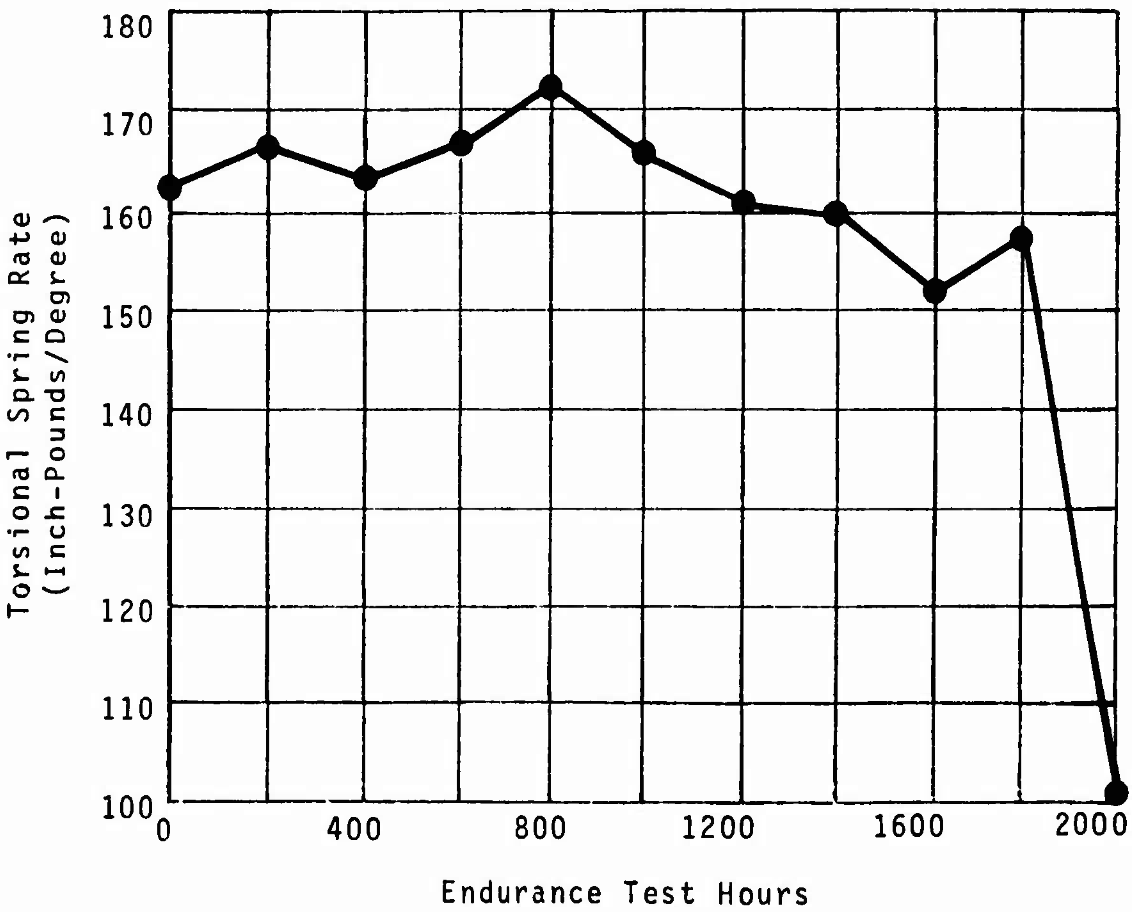


Figure 15. Static Torsional Spring Rate of Test Sample 3 (S/N 006) Without CF Applied.

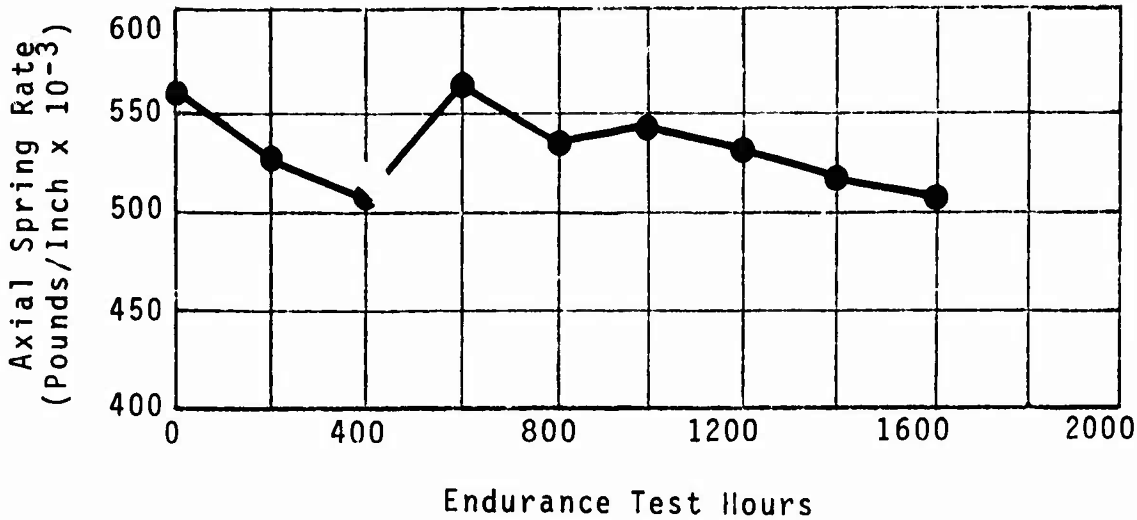


Figure 16. Static Axial Spring Rate of Test Sample 4 (S/N 009).

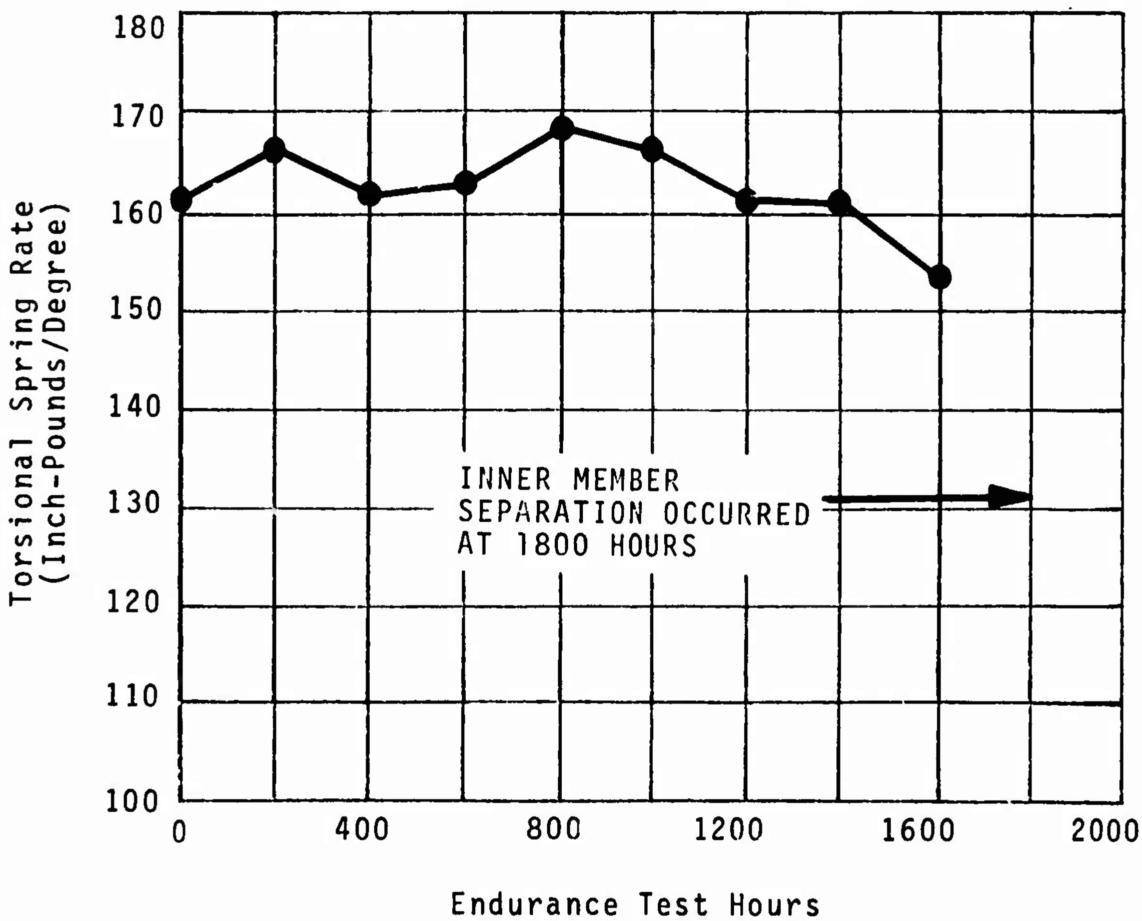


Figure 17. Static Torsional Spring Rate of Test Sample 4 (S/N 009) Without CF Applied.

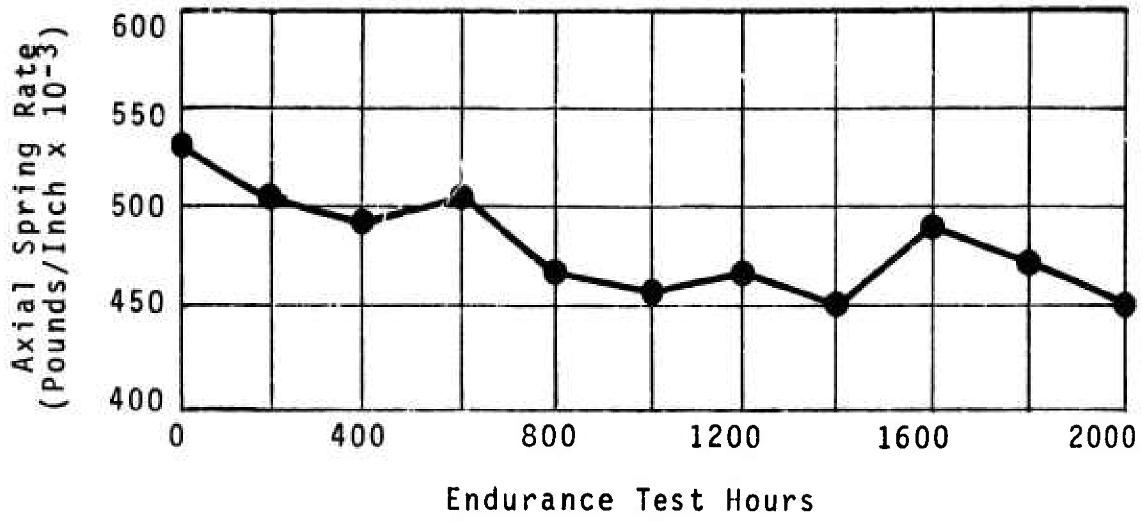


Figure 18. Static Axial Spring Rate of Test Sample 5 (S/N 014).

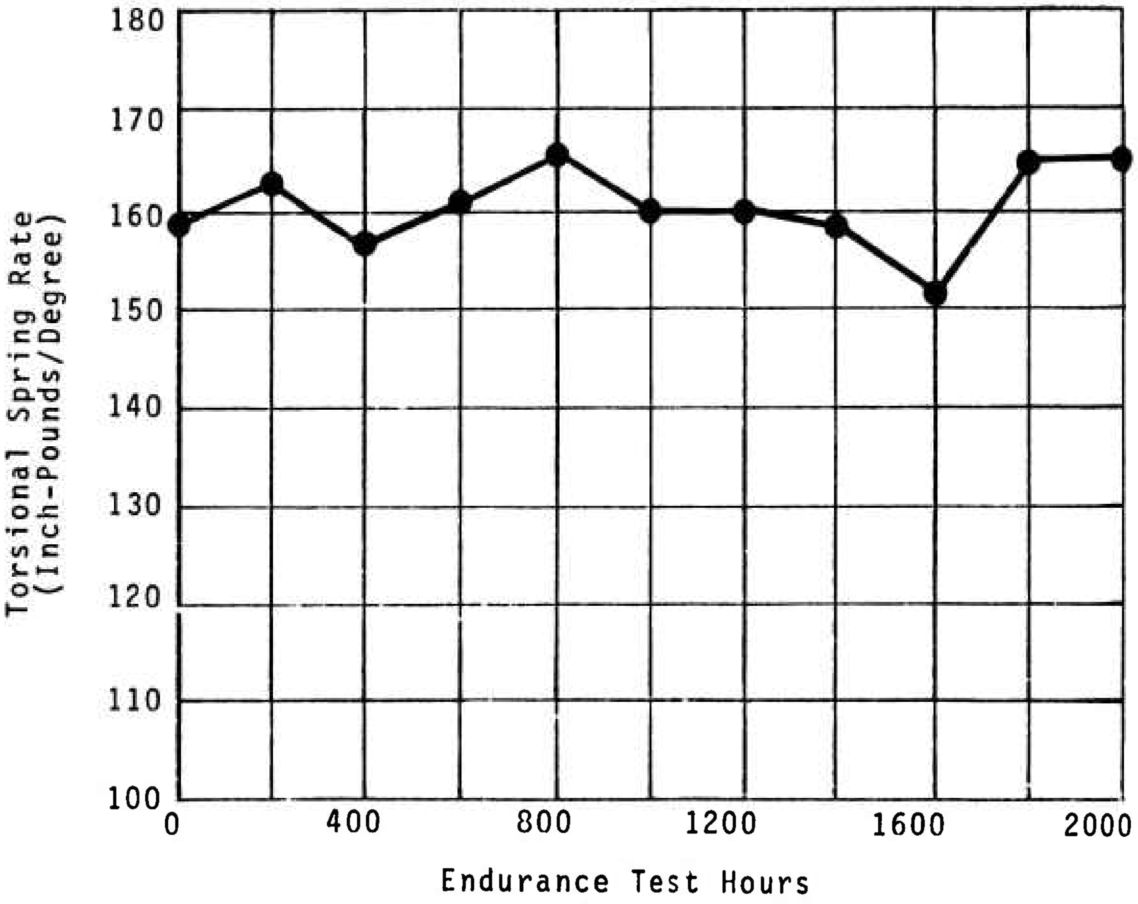


Figure 19. Static Torsional Spring Rate of Test Sample 5 (S/N 014) Without CF Applied.

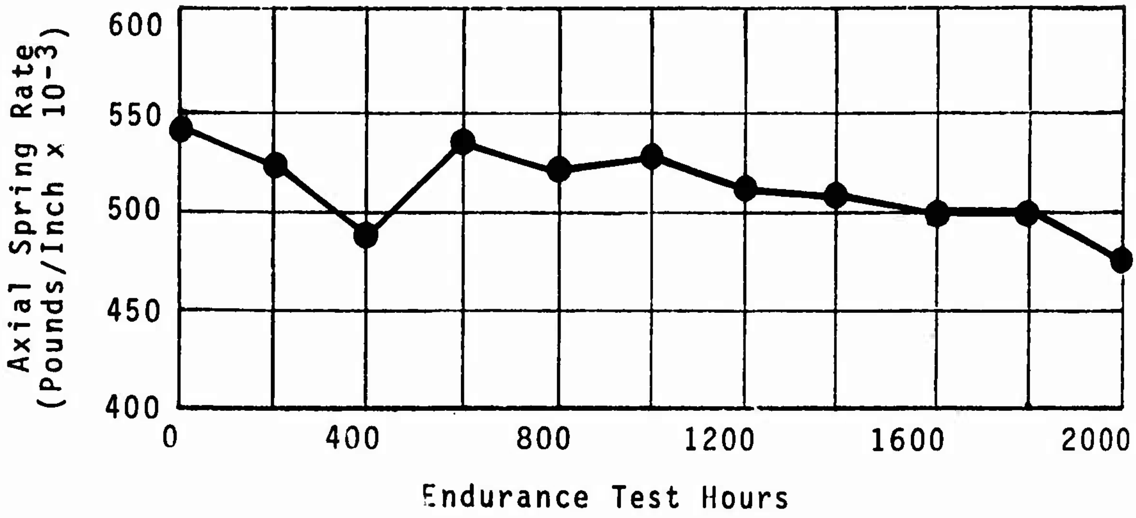


Figure 20. Static Axial Spring Rate of Test Sample 6 (S/N 016).

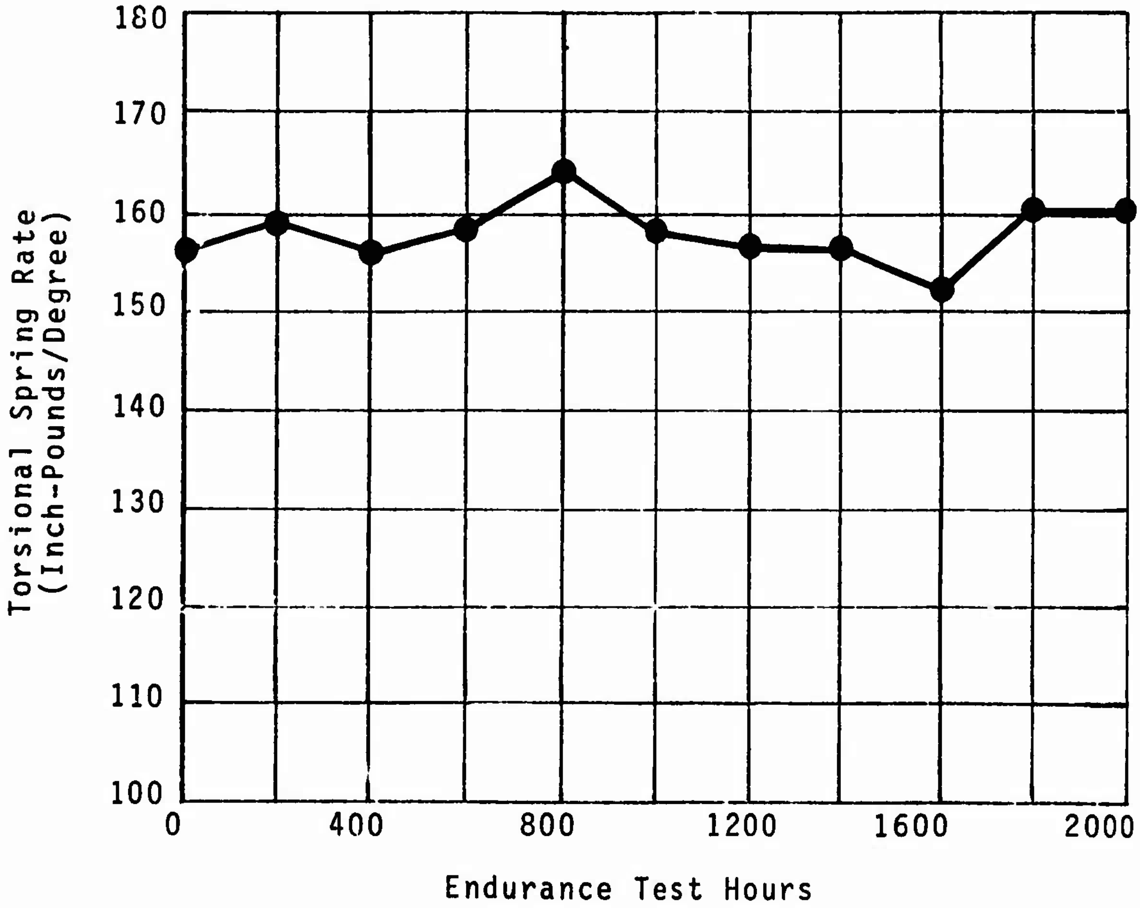


Figure 21. Static Torsional Spring Rate of Test Sample 6 (S/N 016).

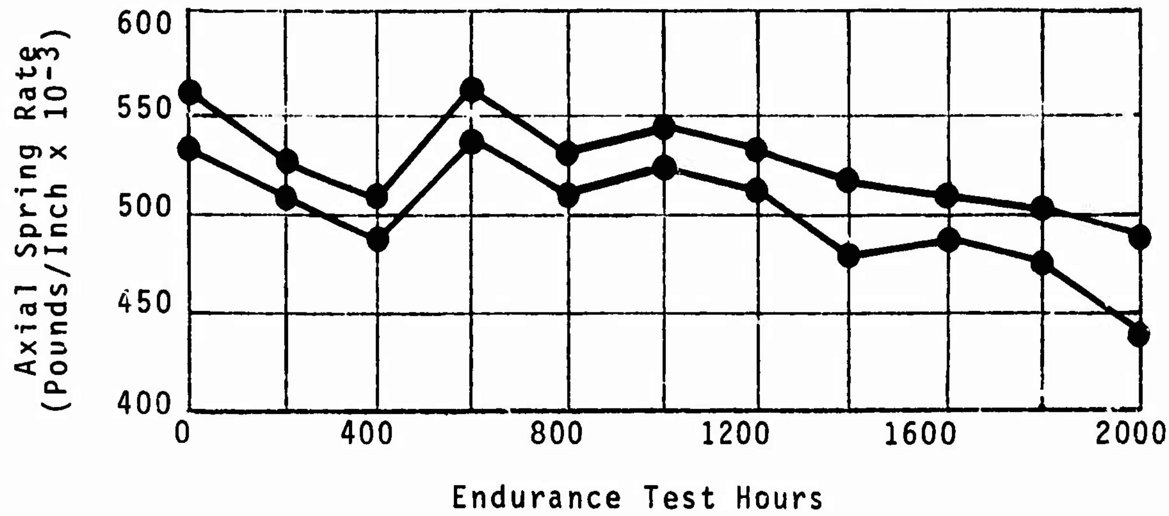


Figure 22. Static Axial Spring Rate Envelope of Test Samples 1 through 6.

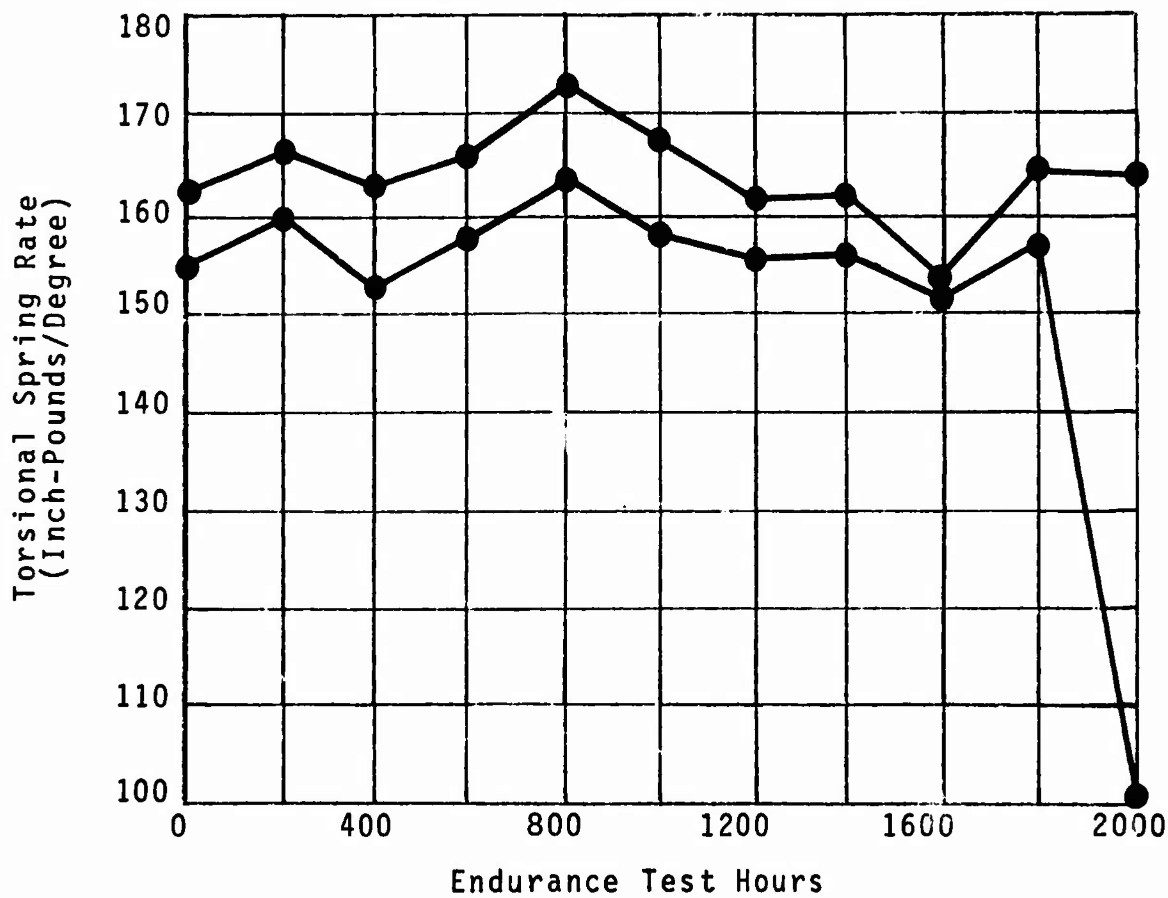


Figure 23. Static Torsional Spring Rate Envelope of Test Samples 1 through 6.

TABLE IV. STATIC TORSIONAL SPRING RATES OF INDIVIDUAL BEARINGS

Endurance Test Hours	Static Torsional Spring Rate (in.-lb/deg)					
	Test Sample Number					
	1	2	3	4	5	6
0	154.8	158.2	162.6	161.5	158.9	156.2
200	160.2	164.9	166.8	166.5	162.7	159.6
400	152.5	158.9	163.1	161.8	157.0	156.1
600	157.8	163.0	166.2	163.0	160.7	160.1
800	163.6	167.2	172.5	168.7	165.8	164.1
1000	157.7	167.9	166.4	166.5	160.0	158.0
1200	155.2	160.6	161.1	161.5	160.0	156.6
1400	155.9	158.6	160.0	161.0	158.5	156.5
1600	152.1	153.8	152.1	153.8	151.4	152.1
1800	159.4	161.9	157.7	-	165.0	160.3
2000	164.8	-	101.3	-	165.3	160.3

TABLE V. STATIC TORSIONAL SPRING RATE OF SAMPLE PAIRS

Endurance Test Hours	Static Torsional Spring Rate (inch-pounds/degree)		
	Test Samples 1 and 2	Test Samples 3 and 4	Test Samples 5 and 6
0	225	228	222
200	232	218	226
400	222	224	216
600	230	221	223
800	270	163	270
1000	279	182	276
1200	216	228	227
1400	208	227	223
1600	218	218	222
1800	223	215*	230

* Test Sample 3 and Serial Number 019 (Spare)

NOTE: Test performed with a 56,000-pound axial load applied to the bearings.

COMPRESSION SET OF INDIVIDUAL SAMPLES

Lengths of the test samples were measured as part of the periodic inspections. The actual dimension measured included a portion of the test machine structure. This additional length was not of interest since it remained unchanged throughout the test. Thus, the change in the overall length was a direct measure of the change in the test sample length. Measurements were taken without the axial load applied in order to determine the amount of axial compression set. Compression set is that portion of the axial deflection due to centrifugal force which is permanent or nonrecoverable upon removal of the load.

Figure 29 is the permanent set envelope of the six endurance test samples during the endurance test. The data at 200 hours was taken in error and is therefore not shown. The amount of compression set which occurred during the first 400 hours is greater than that which occurred during any subsequent 400-hour period. This relatively large initial increase followed by a leveling-off trend is typical of the compression set of elastomeric parts as explained below.

If a relatively large compression stress is applied to an elastomeric part, the deformation which occurs will gradually increase with time, however, the rate of deformation will decrease with time. A gradual internal restructuring of the elastomer occurs as it approaches an equilibrium condition. When the stress is removed, the elastomer does not fully recover immediately and a portion may never be recovered. This initial deformation which is not recoverable is referred to as permanent set. Since the amount of deformation which occurs in an initial time period is greater than that which occurs in any succeeding time period of equal duration, the unrecoverable deformation or permanent set follows the same pattern. Compression set is a normal occurrence with elastomeric bearings subjected to large compression loads for long periods of time. The designer utilizing elastomeric bearings should therefore consider the potential effects of compression set on rotor dynamics.

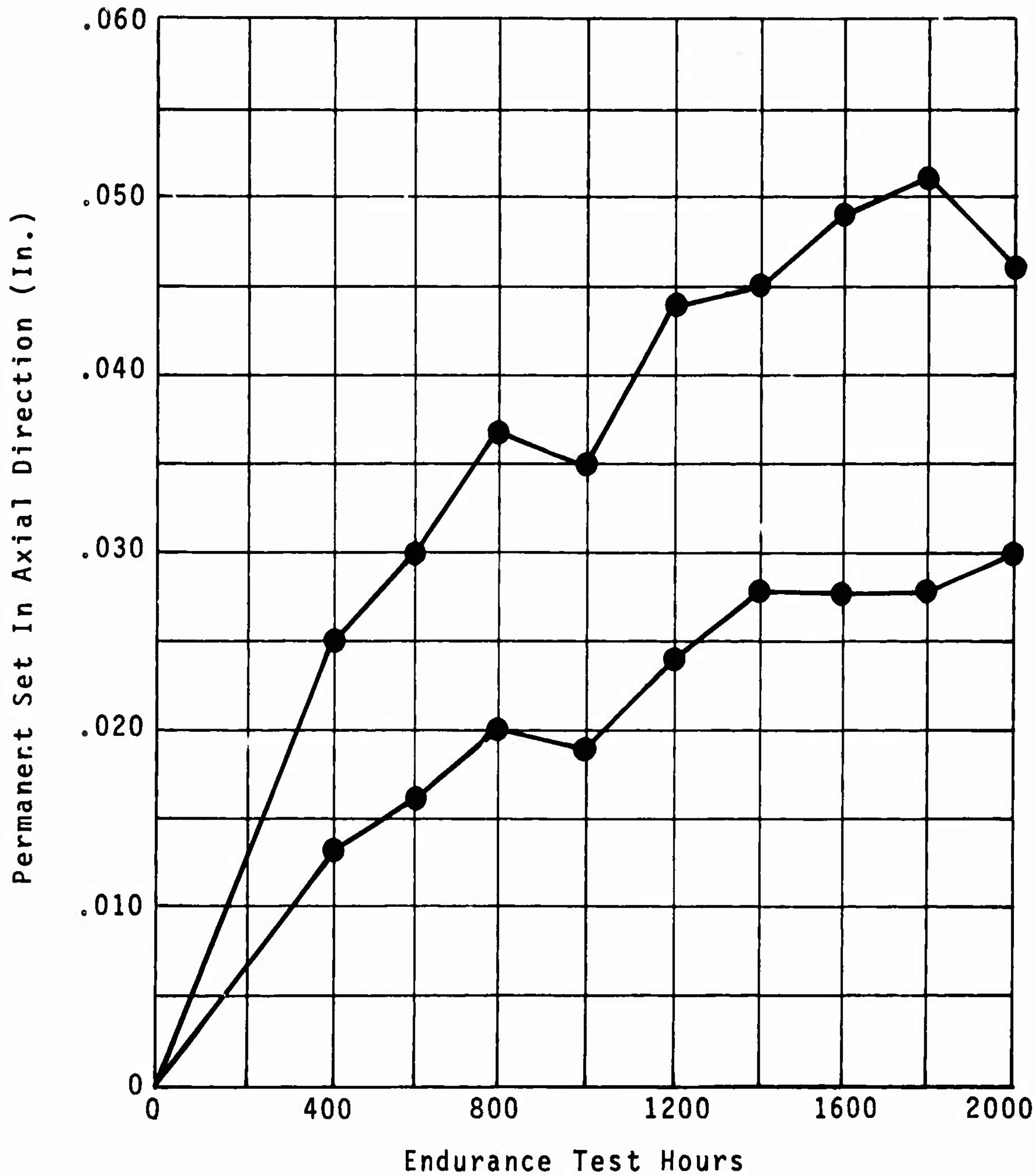


Figure 24. Permanent Set Envelope of Test Samples 1 through 6.

TORSIONAL SET OF INDIVIDUAL SAMPLES

Figure 25 depicts the amount of torsional set which occurred during the endurance test. The data points shown are the average torsional set of the six samples. Measurement of the relative positions of the inner and outer members about the torsional axis determines the amount of torsional set resulting from the static torsional pitch inputs. The amount of torsional set which occurred is relatively small: less than one degree over 2000 hours of testing.

CONCENTRICITY OF INDIVIDUAL SAMPLES

Table VI contains the results of the measurements taken during the periodic test to obtain data regarding the concentricity of the test samples. Ideally, the centers of the inner and outer members would coincide at zero hours, but this does not occur because of normal manufacturing tolerances. The amount of deviation is small and is not considered to affect bearing performance.

Table VI depicts the movement of the inner member center with respect to the theoretically fixed outer member center. The outer member is the origin of a coordinate system. The location of the inner member center with respect to the outer member center is defined by the angle O and the linear distance X.

Examination of the data reveals that there was little movement between the two centers during the endurance test. Although this type of data is interesting, it would appear to be of little use as a monitor of sample condition, particularly because of the difficulty in obtaining it accurately in service.

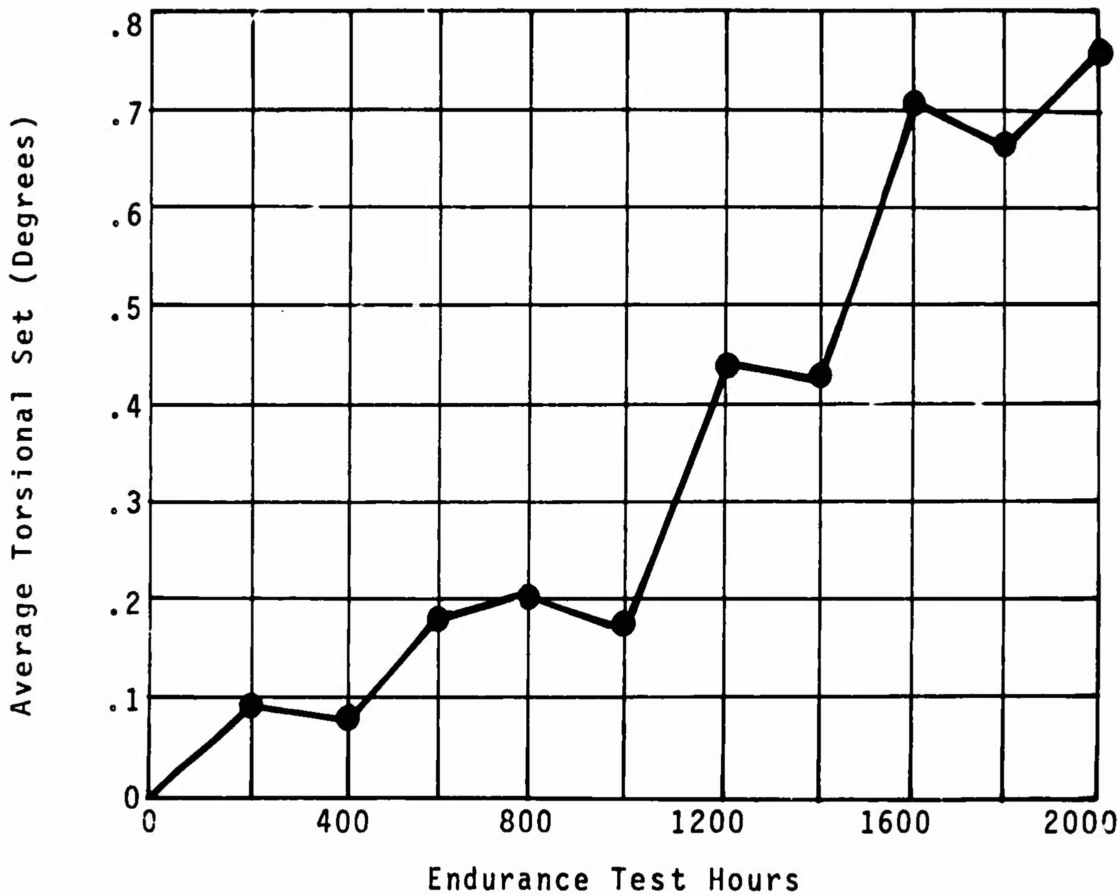
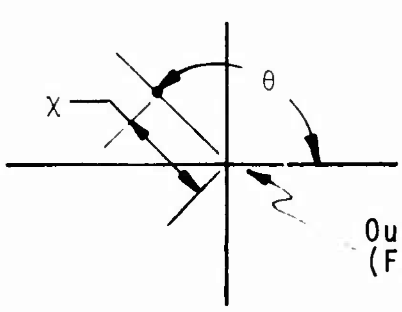


Figure 25. Average Torsional Set of Test Samples 1 through 6.

TABLE VI. CONCENTRICITY BETWEEN INNER AND OUTER MEMBERS

Endurance Test Hours		Test Sample Number 1	2	3	4	5	6
0	χ θ	.034 150°	.050 177°	.031 197°	.025 175°	.054 140°	.022 122°
400	χ θ	.025 154°	.047 174°	.030 203°	.018 167°	.047 140°	.004 135°
600	χ θ	.026 157°	.050 165°	.028 201°	.022 167°	.047 133°	.011 131°
800	χ θ	.025 161°	.047 170°	.025 201°	.018 171°	.035 176°	.022 100°
1000	χ θ	.013 138°	.032 173°	.009 201°	.012 187°	.025 133°	.019 100°
1200	χ θ	.022 153°	.044 169°	.025 203°	.015 169°	.042 142°	.010 127°
1400	χ θ	.020 156°	.037 169°	.022 182°	.018 171°	.043 134°	.021 107°
1600	χ θ	.025 164°	.045 170°	.022 196°	.015 174°	.049 143°	.017 92°
1800	χ θ	.032 154°	.048 168°	.020 195°	- -	.067 132°	.016 108°
2000	χ θ	.024 156°	- -	.021 203°	- -	.047 133°	.017 100°



Location of Inner Member Center is defined by an angle, θ and a linear distance, χ.

Outer Member Center (Fixed)

VISUAL INSPECTION OF INDIVIDUAL SAMPLES

In addition to the photographs taken at 200-hour intervals, the appearance of the test samples was monitored periodically. Significant occurrences, such as the initial evidence of abrasion or a rapid change in sample appearance, were noted. A detailed inspection of the samples while installed in the test machine was difficult because of surrounding fixture. The need for fixture rigidity resulted in a relatively massive structure which surrounded the test samples on all sides.

Tables VII, VIII, and IX contain the visual inspection records of the three test sample pairs. Examination of the records indicates that test sample 3 was the first sample to show evidence of abrasion. This occurred after approximately 503 hours of endurance testing. Test samples 2 and 4 began to abrade after 790 hours of testing. The remaining three samples, test samples 6, 5, and 1, began abrading elastomer after 952, 997, and 1060 hours respectively.

The initial abrasion on all samples occurred in the innermost elastomer layer. The abrasion was rather uniformly distributed around the circumference of the part and therefore could not be directly attributed to the effects of the radial load. The abrasion appeared to be the result of the combined effects of compression strains due to axial and radial loads and shear strains resulting from pitch motion.

As is typical of elastomeric bearing fatigue, the initial evidence of elastomer abrasion resembled the crumbling of an eraser. In the absence of a large airflow across the bearing surface, these particles tend to build up on the surface. This abrasion continued and in some instances became hairlike in appearance. As the elastomer loss continued, it became possible to measure the depth of separation.

Test samples 3 and 4 were removed from the test machine at 952 hours to allow close inspection. At this time, the depth of separation in the innermost layer was measured. The remaining four samples were not removed in order to minimize this unscheduled downtime.

Slight nicks were noted in some areas of the major metal parts due to repeated installation and removal in the test machine. No shim damage was noted.

TABLE VII. VISUAL INSPECTION RECORD OF TEST SAMPLES 1 AND 2

Endurance Test Hours	Comments on Appearance: Test Sample 1 (S/N 004)	Comments on Appearance: Test Sample 2 (S/N 005)
148	No change from new	No change from new
172	No change	No change
503	No change	No change
790	No change	Slight abrasion noted in innermost elastomer layer.
952	No change	Abrasion continuing
1060	Slight abrasion noted in innermost elastomer layer.	Abrasion continuing
1800	Depth of elastomer loss in innermost layer is 1.4 inches. Layers 2 through 10 show abrasion but no appreciable depth.	Depth of elastomer loss in innermost layer is 1.4 inches. Layers 2 through 10 show abrasion but no appreciable depth.
2000	Depth of elastomer loss in innermost layer is 1.4 inches. All layers show abrasion. Sections 1, 7, and 8 most severe.	Inner member nearly separated. Radial load has cracked shim number 1 and bent shim number 2. All sections show abrasion. Sections 1, 5, 6, 7, and 8 most severe.

TABLE VIII. VISUAL INSPECTION RECORD OF TEST SAMPLES 3 AND 4

Endurance Test Hours	Comments on Appearance: Test Sample 3 (S/N 006)	Comments on Appearance: Test Sample 4 (S/N 009)
148	No change from new	No change from new
172	No change	No change
503	Slight abrasion noted in innermost elastomer layer	No change
555	Slight increase in amount of abrasion.	No change
790	Abrasion continuing	Slight abrasion noted in innermost layer.
952	Abrasion noted in layers 1 through 10. Depth of elastomer loss is .2 to .4 inch in first layer.	Abrasion noted in layers 1 through 10. Depth of elastomer loss is .2 inch in first layer.
997	Abrasion has become hairlike and slightly more severe.	No change - abrasion continuing.
1400	Depth of elastomer loss is .8 inch in first layer.	Abrasion continuing - no depth measurement taken.
1600	Depth of elastomer loss is 2.0 inches in first layer.	Abrasion continuing
1800	Depth of elastomer loss is 2.0 inches in first layer.	Failure - inner member separation due to loss of elastomer.

TABLE VIII - CONTINUED

Endurance Test Hours	Comments on Appearance: Test Sample 3 (S/N 006)	Comments on Appearance: Test Sample 4 (S/N 009)
1800 (con't)	Layers 2 through 10 show abrasion but no appreciable depth.	
2000	Depth of elastomer loss exceeds 2.0 inches in first layer. All sections show abrasion. Sections 1 through 7 most severe. Depth of elastomer loss in section 7 is .5 inch.	Sample failed at 1800 hours.

TABLE IX. VISUAL INSPECTION RECORD OF TEST SAMPLES 5 AND 6

Endurance Test Hours	Comments on Appearance: Test Sample 5 (S/N 014)	Comments on Appearance: Test Sample 6 (S/N 016)
148	No change from new	No change from new
172	No change	No change
503	No change	No change
790	No change	No change
952	No change	Slight abrasion noted in innermost elastomer layer.
1997	Slight abrasion noted in innermost elastomer layer.	Abrasion continuing
1032	Abrasion noted in sixth layer.	Abrasion continuing
1800	Depth of elastomer loss is 1.5 inches in first layer.	Depth of elastomer loss is 1.0 inch in first layer.
2000	Depth of elastomer is 1.8 inches in Section 1 and .7 inch in Section 7. All sections show abrasion.	Depth of elastomer loss is 1.3 inches in Section 1. All sections show abrasion.

FAILURE SUMMARY

None of the test samples failed due to the failure criterion of a 40% loss of torsional spring rate. With the exception of test sample 3, the torsional spring rates of the samples did not decrease significantly. This is explained by the fact that the primary elastomer loss, and therefore spring rate loss, was confined to the innermost section. The remaining sections did not deteriorate significantly, and therefore the overall bearing spring rate was relatively steady with time.

Test sample 4 was the first sample to fail, with failure occurring after 1800 hours of endurance testing and during the performance of 1800-hour manual conditions. Upon removal from the test machine after completion of the manual conditions, the inner member completely separated from the flexing element. The loss of elastomer due to abrasion resulted in a significant decrease in the shear load area of the innermost section. As a result, the bearing was unable to withstand the manual conditions and failed in shear. Inspection of the failed area revealed a good bond.

The second failure occurred during the manual conditions after 2000 hours of endurance testing. Test sample 2 experienced inner member separation after completion of 750 cycles of the first manual condition: the ± 12-degree pitch input. The cause of failure was identical to that of test sample 4.

Test sample 3 may be considered to have failed even though it did not fulfill a strict interpretation of the failure criterion. The torsional spring rate at 2000 hours was approximately 37% below the initial value, and the depth of elastomer loss in the innermost section exceeded 2.0 inches. Good engineering judgment would not allow this bearing to continue on test beyond 2000 hours.

The remaining three samples did not fail according to the established failure definition. In spite of the loss of elastomer from abrasion, all three samples were able to support radial and axial loads and to accommodate torsional motion. None of the six samples experienced a failure of the inner and outer attachment metal parts.

RELIABILITY ANALYSIS

A common statistical technique used in the analysis of test data is the Weibull analysis technique. This method is frequently used in the ball and roller bearing industry to estimate the frequency distribution of fatigue failures. A sample of a total bearing population is tested, and the Weibull analysis predicts the percentage of bearings which will fail in a given time. The time by which 10 percent of the bearings will have failed is referred to as the B-10 life and is frequently used as a measure of a bearing performance. A Weibull analysis of the previously tested LM-726-1 bearing resulted in a B-10 life of 812 hours.

A detailed discussion of the Weibull analysis technique is beyond the scope of this report. However, it is pointed out that the number of test samples available for analysis affects the accuracy of the analysis. Generally speaking, meaningful results can be obtained only with a sample size of six, all tested to failure. With only three failures, two of which occurred at the same time, a Weibull analysis of the LM-726-4 test results would have little meaning. However, if testing had continued beyond 2000 hours to result in three additional failures, the resulting B-10 life would have been in excess of 1800 hours.

PHOTOGRAPHIC RECORD OF ENDURANCE TEST

The photographs designated Figures 26 through 54 depict the progression of the fatigue damage on the six endurance test samples. Emphasis has been placed on test samples 1 and 3. Test sample 3 was the first sample to show indications of abrasion and remained the most severely abraded sample throughout the test. Test sample 1 is shown because its appearance was typical of the remaining four samples.

The change in appearance of the abrasion from eraserlike particles to hairlike is visible, as well as the depth of separation which occurred with continuing elastomer abrasion. Prior to photographing the bearings at 1800 hours, the abraded elastomer was brushed away from the surface to allow a closer examination of the extent of fatigue damage.

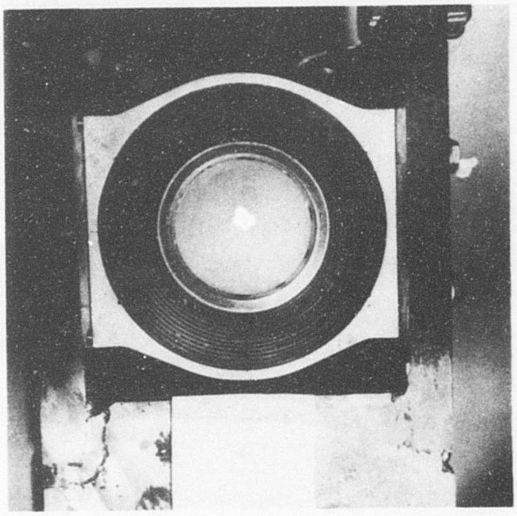


Figure 26. Test Sample 1 (S/N 004) After 400 Hours of Endurance Testing. (No deterioration visible. Appearance typical of all samples.)

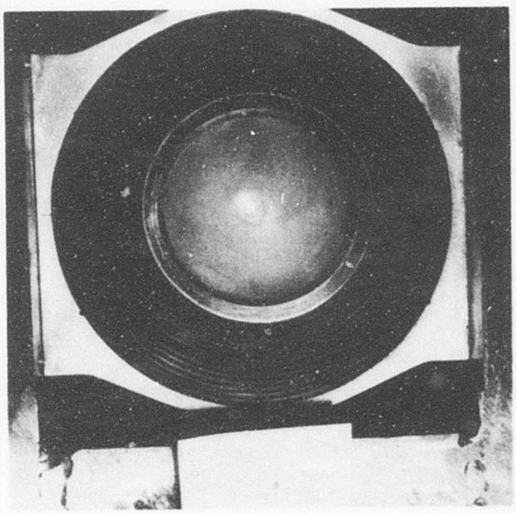


Figure 27. Test Sample 1 (S/N 004) After 600 Hours of Endurance Testing. (No deterioration visible. Appearance typical of all samples.)

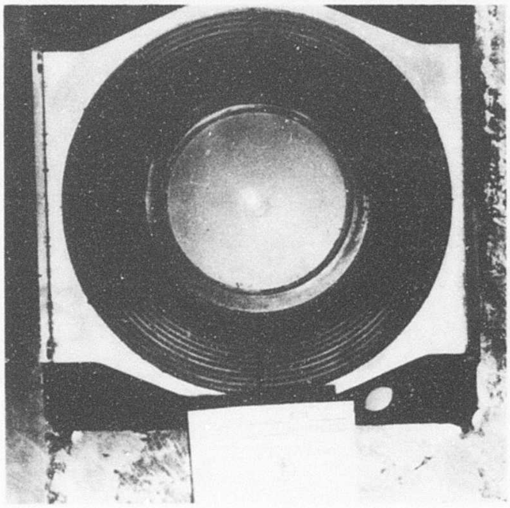


Figure 28. Test Sample 3 (S/N 006) After 600 Hours of Endurance Testing. (Slight elastomer abrasion visible in innermost elastomer layer.)

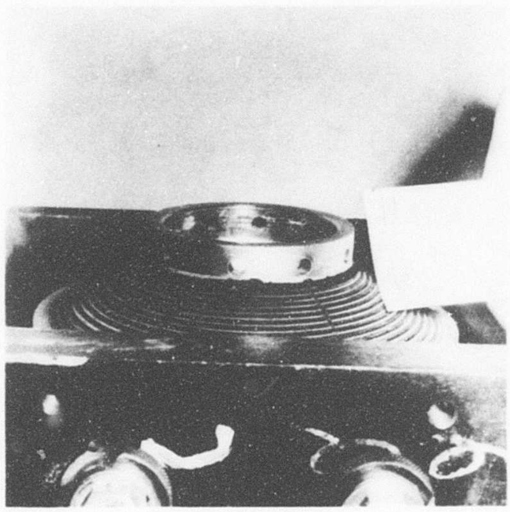


Figure 29. Test Sample 3 (S/N 006) After 600 Hours. (Elastomer abrasion visible in innermost layer, extending around entire circumference.)

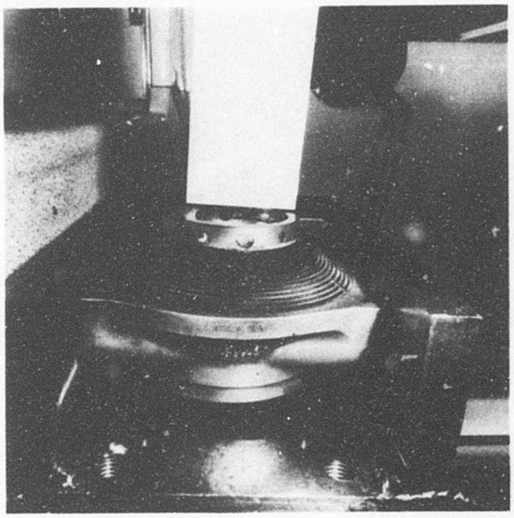


Figure 30. Test Sample 3 (S/N 006) After 800 Hours of Endurance Testing. (Most severe abrasion occurring in innermost layer, but abrasion can now be seen in layers 2 through 10.)

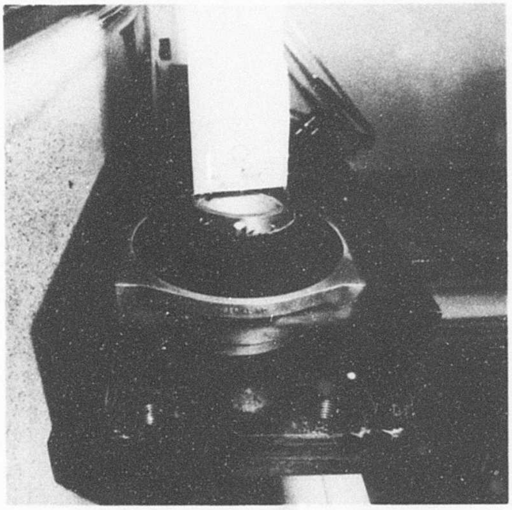


Figure 31. Test Sample 1 (S/N 004) After 1000 Hours of Endurance Testing. (Slight abrasion visible in sections 1 through 10.)

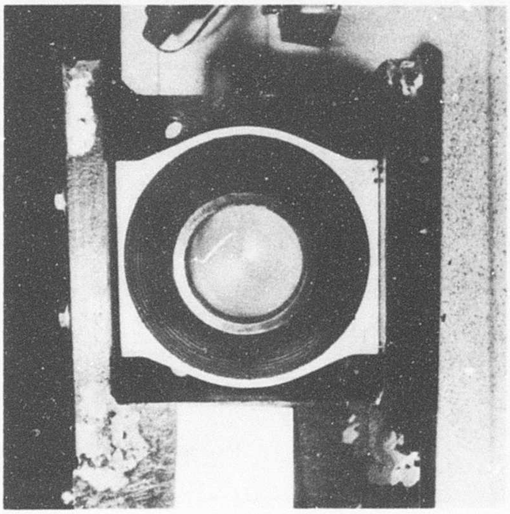


Figure 32. Test Sample 2 (S/N 005) After 1000 Hours of Endurance Testing.

Figure 33. Test Sample 3 (S/N 006) After 1000 Hours of Endurance Testing. (This sample considered to be the most severly damaged at this point.)

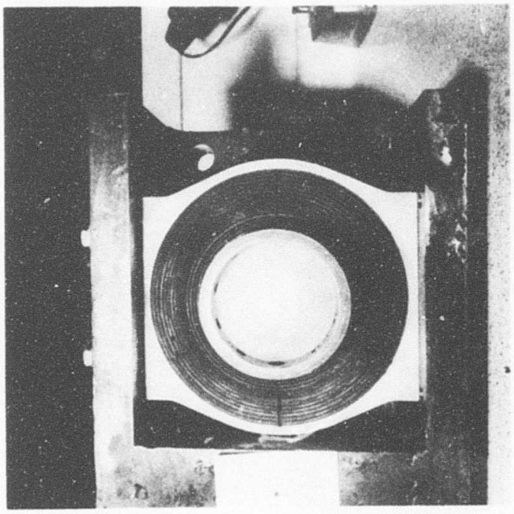


Figure 34. Test Sample 4 (S/N 009) After 1000 Hours of Endurance Testing.

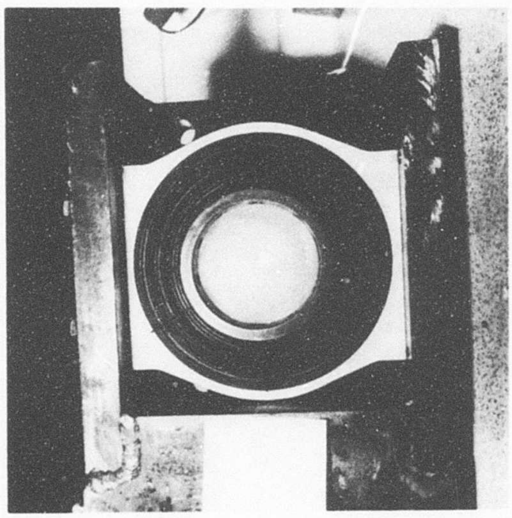


Figure 35. Test Sample 5 (S/N 014) After 1000 Hours of Endurance Testing.

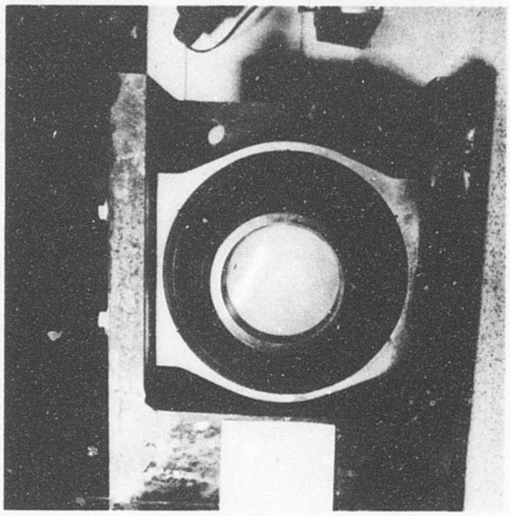


Figure 36. Test Sample 6 (S/N 016) After 1000 Hours of Endurance Testing.

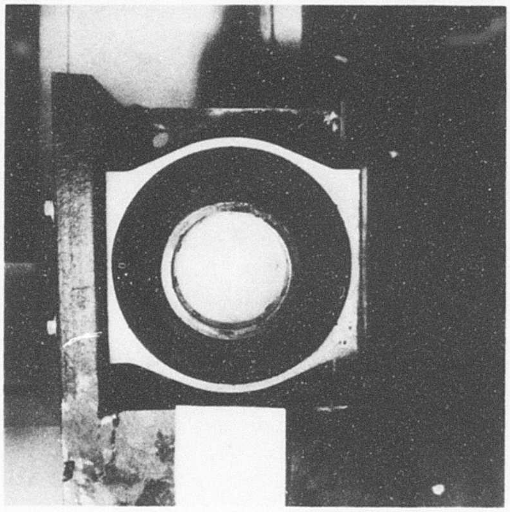


Figure 37. Test Sample 1 (S/N 004) After 1200 Hours of Endurance Testing.

Figure 38. Test Sample 2 (S/N 005) After 1200 Hours of Endurance Testing.

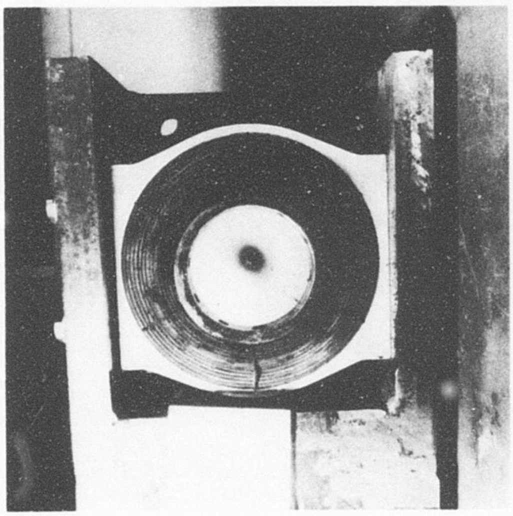


Figure 39. Test Sample 3 (S/N 006) After 1200 Hours of Endurance Testing. (Note the hairlike abrasion of elastomer.)

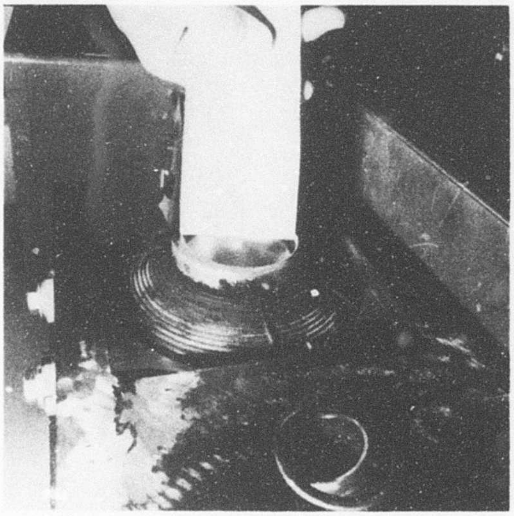


Figure 40. Test Sample 3 (S/N 006) After 1200 Hours of Endurance Testing. (Note the hairlike abrasion of elastomer.)

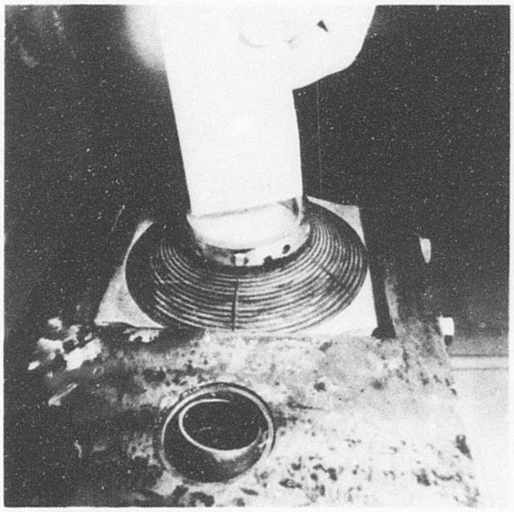


Figure 41. Test Sample 4 (S/N 009) After 1200 Hours of Endurance Testing.

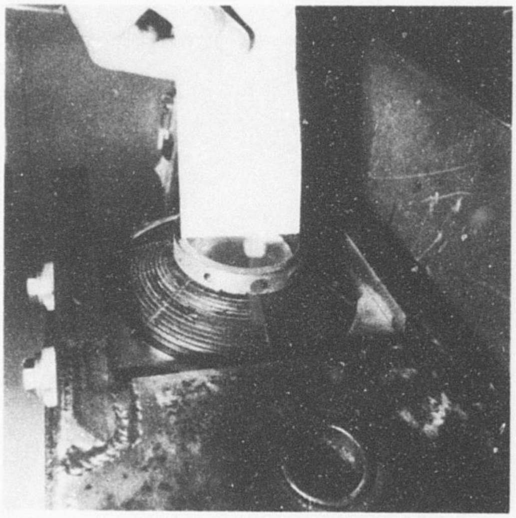


Figure 42. Test Sample 5 (S/N 014) After 1200 Hours of Endurance Testing.

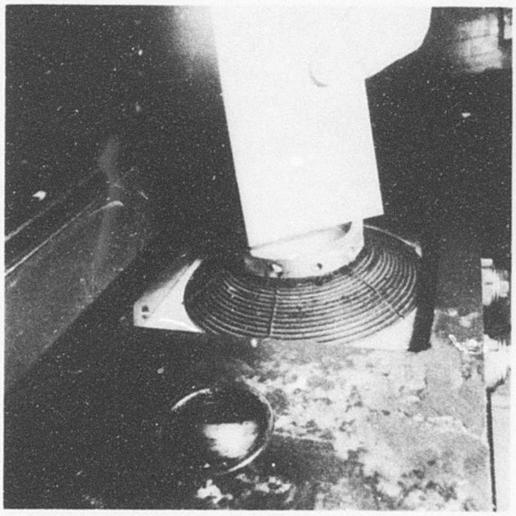


Figure 43. Test Sample 6 (S/N 016) After 1200 Hours of Endurance Testing.

Figure 44. Test Sample 1 (S/N 004) After 1400 Hours of Endurance Testing. (Appearance is typical of Test samples 2, 4, 5, and 6.)

Figure 45. Test Sample 3 (S/N 006) After 1400 Hours of Endurance Testing. (This sample is the most severely damaged at this point of the test. A depth of separation is visible in first layer in left center of photo.)

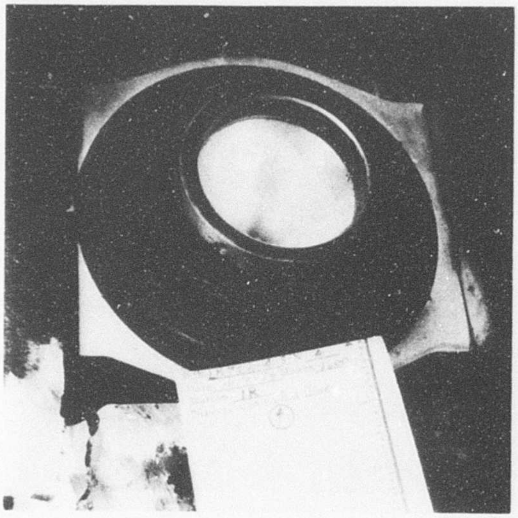


Figure 46. Test Sample 1 (S/N 004) After 1600 Hours of Endurance Testing. (Appearance is typical of test samples 2, 4, 5, and 6.)

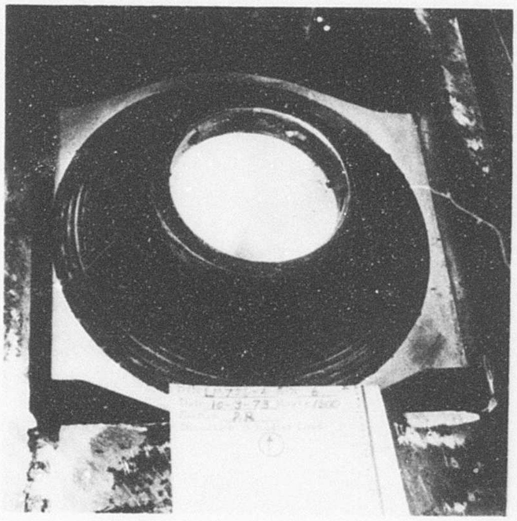


Figure 47. Test Sample 3 (S/N 006) After 1600 Hours of Endurance Testing. (Most severely damaged sample. Note depth of separation visible in left center of photograph.)

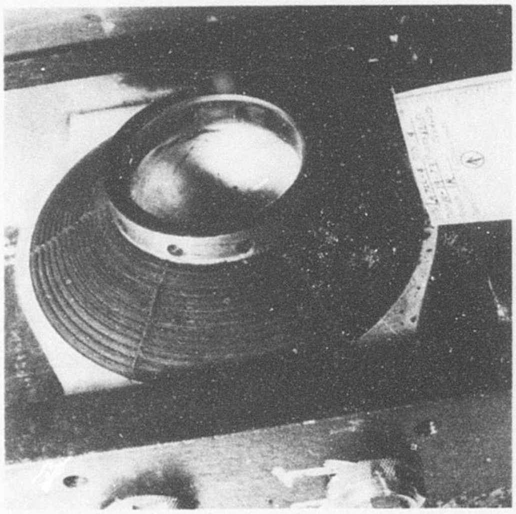


Figure 48. Test Sample 1 (S/N 004) After 1800 Hours of Endurance Testing. (Loose elastomer has been brushed away to allow close examination. Note depth of separation visible in first layer.)

Figure 49. Test Sample 2 (S/N 005) After 1800 Hours of Endurance Testing. (Loose elastomer has been brushed away to allow close examination.)

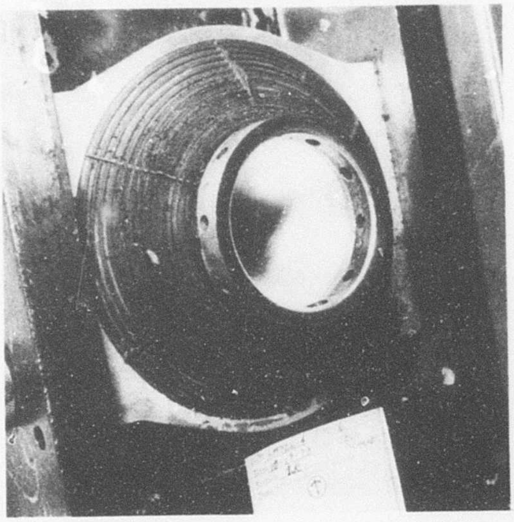


Figure 50. Test Sample 3 (S/N 006) After 1800 Hours of Endurance Testing. (Loose elastomer has been brushed away. Note depth of separation visible in first layer.)

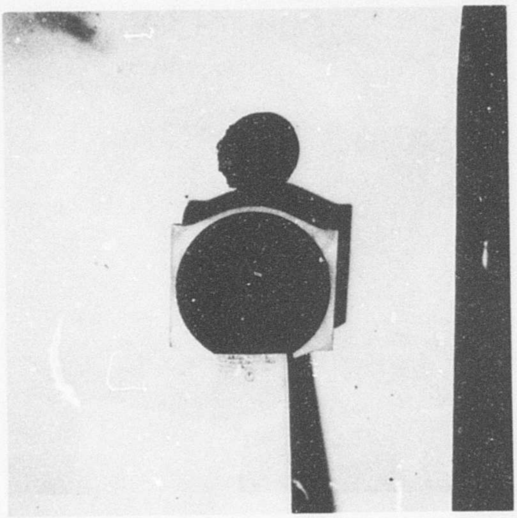


Figure 51. Test Sample 4 (S/N 009) After 1800 Hours of Endurance Testing. (Loose elastomer has been brushed away to allow close examination. Note depth of separation visible in first layer.)

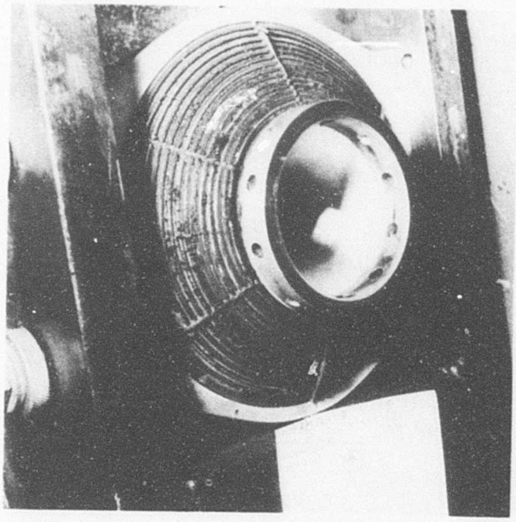


Figure 52. Test Sample 5 (S/N 014) After 1800 Hours of Endurance Testing. (Loose elastomer has been brushed away to allow close examination. Note depth of separation visible in first layer.)

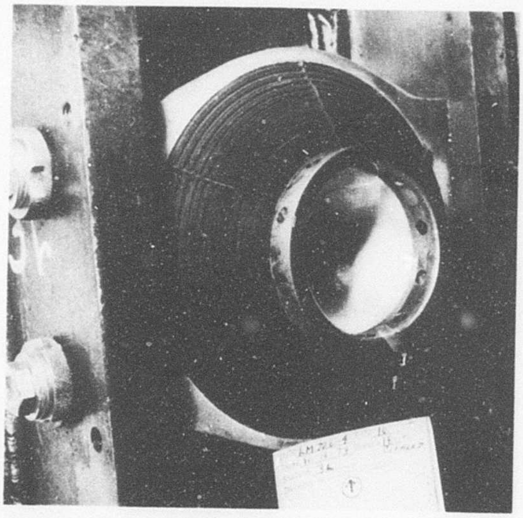


Figure 53. Test Sample 6 (S/N 016) After 1800 Hours of Endurance Testing. (Loose elastomer has been brushed away to allow close examination.)

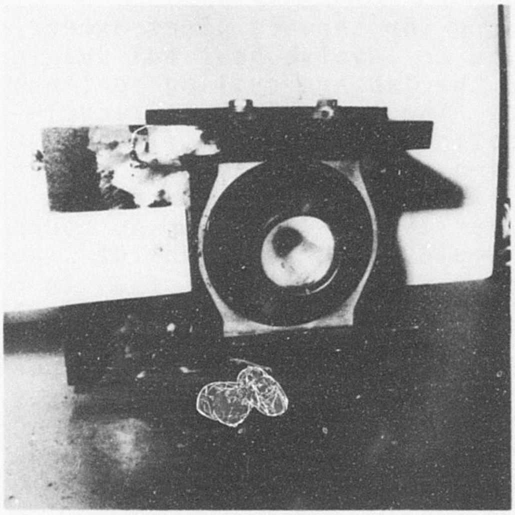


Figure 54. Test Sample 4 (S/N 009) After 2000 Hours of Endurance Testing. (Appearance typical of all samples.)

RECOMMENDED INSPECTION AND REPLACEMENT CRITERIA

A laboratory endurance test such as that conducted on the LM-726-4 is useful in the establishment of guidelines for inspection and replacement criteria. This type of test is particularly successful in establishing the mode of failure which can be expected to occur in service. However, laboratory testing has proven to be conservative in establishing specific service lives. In several instances, service lives of elastomeric bearings have shown a considerable improvement over their laboratory fatigue lives. There are several possible reasons for this discrepancy.

The primary reason for service lives exceeding laboratory lives is believed to involve heat buildup in the bearing. The bearings in the lab are cycling continuously with little downtime. The test block or recycle time often exceeds the duration of a typical flight. As a result, the amount of time spent at the large motion conditions which generate excessive heat is unrealistically large. The test block for the LM-726-4 was 40 hours, where a typical flight would be on the order of 1 hour. In addition, the amount of cooling airflow in service would exceed that experienced with small fans in the laboratory. The shorter "flight" time, the greater cooling airflow, and the noncontinuous running would be expected to result in a cooler running bearing and thus greater life.

Based on the endurance test of the LM-726-4, the following inspection guidelines can be established:

--Each bearing should be visually inspected for deterioration at periodic intervals, perhaps before each flight, although flight experience may dictate less frequent inspections.

--The initial deterioration will most likely occur in the innermost sections, therefore, this area should receive particularly close inspection.

—The first evidence of deterioration will generally have the appearance of abraded eraser particles. The large airflow around the bearings may prevent a buildup of these particles, necessitating a particularly close examination of the elastomer surface to detect deterioration.

--Exposed surfaces of the shims should be inspected visually for nicks, gouges, or cracks. A cracked

shim generally results from abnormal shim flexing in an area where a large elastomer loss has left the shim unsupported. This will usually occur late in the bearing's life cycle. A cracked shim is a sufficient cause for bearing replacement.

--Abrasion of elastomer will continue to progress in the area where it was first detected and will begin to spread outward to other areas. As the abrasion continues, a measurable depth of separation will occur. Additional experience will allow the establishment of guidelines regarding the depth of elastomer loss and the remaining service life.

--The axial deflection of the bearing under the normal centrifugal force increased with increasing service time. If a means of monitoring blade travel could be established, this together with allowable axial deflection limits could be used as a monitor of the bearings remaining service life. Bearing permanent compression set might also be used as a monitor.

--The torsional spring rate of the LM-726-4 did not exhibit a clear trend. This combined with the difficulty of measurement in service makes the monitoring of torsional spring rate somewhat unattractive as an inspection technique.

--The monitoring of bearing torsional set or concentricity of inner and outer members does not appear to be of value as an inspection technique. Both properties would be difficult to measure and, in addition, the concentricity does not exhibit a consistent behavior.

CONCLUSIONS

The design modifications incorporated in the LM-726-4 bearing as a result of the previous LM-726-1 testing were successful in increasing the laboratory fatigue life to an acceptable level. The greater than two-to-one increase in Weibull B-10 life exceeded the goal of a 50 percent improvement.

The modification to the flexing element contour which was incorporated to provide better radial load distribution was successful. The initial abrasion was not concentrated in the radial load path but was instead more evenly distributed around the entire circumference. This remained the case through the entire test, as the areas of most severe abrasion were randomly distributed rather than concentrated in the radial load path as on the previously tested LM-726-1.

The lower overall shear strains resulting from the increase in available space for elastomer also contributed to the improved fatigue life. The initial elastomer abrasion did not occur until the 500- to 1000-hour range, whereas the LM-726-1 bearing was abrading within the first 200 hours of test. Although a portion of this improvement was due to the improved radial load carrying capability, the reduction in overall shear strains was also a contributing factor.

The mode of failure demonstrated was similar to the LM-726-1 bearing and typical of elastomeric bearings in general. The initial indications of failure were small eraserlike particles of elastomer which abraded out in the area of highest combined compression and shear strain. In the case of the LM-726-4, this occurred in the innermost section. The abrasion continued gradually in this area and gradually progressed to other elastomer layers. Initially the abrasion was primarily surface abrasion, but as the test continued, a measurable depth of elastomer loss occurred. Shim failures may occur due to the loss of elastomer which results in shim flexing, although none occurred during the LM-726-4 test. A large amount of elastomer loss will weaken a section of the flexing element, rendering it incapable of supporting relatively large torsional inputs. This mode of failure occurred with test samples 2 and 4.

The six test samples demonstrated consistent performance with regard to spring rate performance. The values

obtained for the torsional and axial spring rates were closely grouped both as new samples and throughout the fatigue test. Although all of the bearings were not tested to failure, it is expected that the failures would occur in the 1800- to 2400-hour range. On this basis, it can be concluded that consistent performance would be obtained in service.

The fatigue life of the LM-726-4 in service can reasonably be expected to exceed 1800 hours. Typically, the service life of an elastomeric bearing will exceed the laboratory fatigue life for several reasons. The continuous 24-hour-per-day cycling imposed in the laboratory is more severe, particularly with respect to internal heating. The test block duration which determines the length of continuous running at the more severe conditions can also result in unrealistic heating. Ideally, the test block duration should be the length of a typical flight so that the severe conditions which generate excessive bearing temperatures will be of short duration and thereby minimize the heating of the elastomer.

Based on the endurance testing performed, the LM-726-4 is considered suitable for flight service evaluation, with visual inspections at periodic intervals considered suitable as a monitor of bearing condition.

RECOMMENDATIONS

The LM-726-4 elastomeric bearing has demonstrated acceptable performance characteristics and fatigue life for utilization as a pitch change bearing in the Bell Model 540 rotor. A field service evaluation to determine the correlation between laboratory fatigue life and field service life is recommended as the next logical task in the qualification of the LM-726-4 bearing.

LITERATURE CITED

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